Extraplanetary Solar Power

The Most Promising Sustainable Energy Option You Never Heard Of

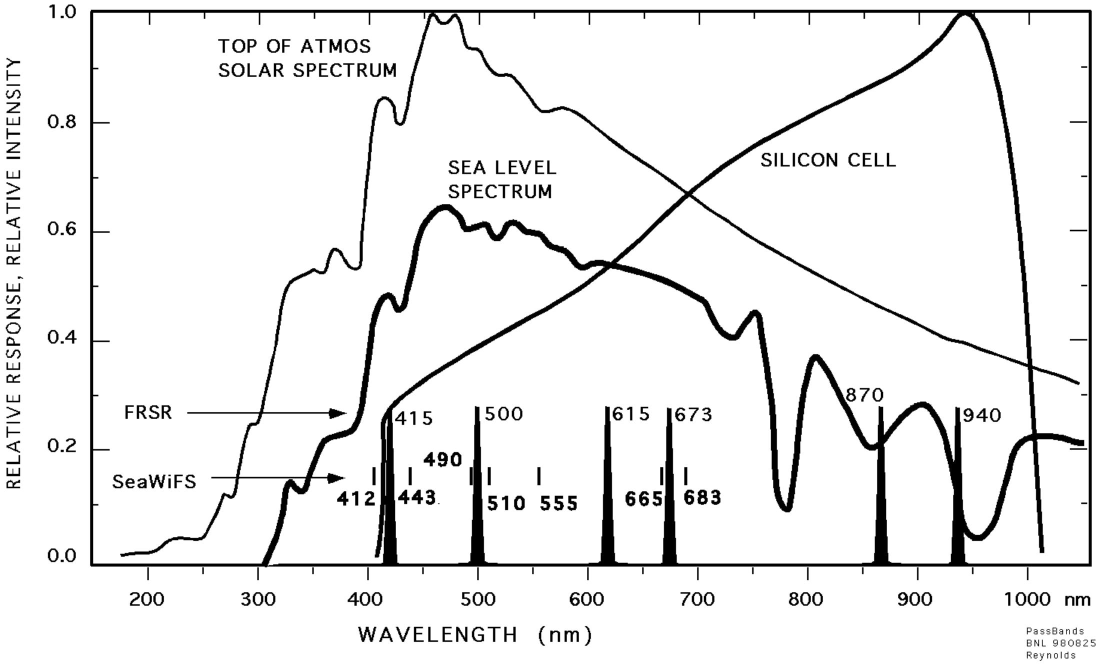
Jerrad Pierce

1.1.0 Overview

Among the suite of currently available sustainable energy options solar power has long been a favorite. Universally available well-matched to modern load patterns (Landis, 1997) and seemingly inexhaustible, solar power would seem to be “quite possibly, the world’s perfect fuel.” Alas closer examination reveals many impediments to its wide adoption including diurnal, seasonal, and geographic variabilities as well as low density and poor conversion efficiency with commercially available technologies. In his 1968 landmark paper “Power from The Sun: Its Future” Peter Glaser outlines a novel solution which addresses many of the problems of traditional solar energy systems. Glaser proposed harnessing solar power via satellites in orbit for transmission to Earth. There would be appear to be many advantages to such a system including: avoiding seasonal variation in solar flux on the Earth’s surface, placing the large solar collection apparatus “out of the way” in space, and harvesting sunlight at its full power, see Figure 1-1. Atmospheric transmission losses are large and numbers cited for the reduction of power by the atmosphere range from 50% (Mitsubishi, 2003) to 88% (Silber, 2002). Note that shorter wavelengths contain more energy, and these variations in estimates are likely due to differences in the region of the spectrum examined.

There have been many variations on theme initially proposed by Glaser and they are referred to by a variety of many names including satellite solar power (SSP), space solar power (also SSP), solar power satellite (SPS), and lunar solar power station/system (LSPS). This paper will refer to the set of schemes by the occasionally used term of extra-planetary solar (power) or XPS, in order to be all-encompassing and place emphasis on the key concept and the four common parts: a space-based platform, a solar conversion system on the platform, a transmitter on the platform, and a an earth-bound receiver. Many systems also incorporate relay satellites or mirrors to increase reliability.

Figure. 1-1 Atmospheric losses



Note. From *BNL-PRP Details* by Reynolds, 1998, [WWW document] URL http://www.gim.bnl.gov/instruments/prp/PrpDetails.html

Most XPS research initially focused on North America though attention has also been given to applications for Europe (Ruth & Westphal, 1980). Japan has shown great interest in XPS and incorporated XPS into its Sunshine program, adopted after the 70's oil embargoes, with projections of a demonstration system by 2010 (Glaser, 1993. Silver, 2002). In fact, some even see Japan as a potential energy exporter if it follows through, given the lead it would have on other nations (Glaser, 1993).

Since its conception XPS has always been largely deemed to be within in the realm of current technical feasibility, yet it remains largely unpursued. Several advocates are frustrated by this and question funding priorities given that $1 billion per year invested in fusion in the United States while XPS essentially receives none. NASA's "Fresh Look" by Mankins describes several XPS systems with price tags of $6 to $8 billion that would generate 250 MW of scalable commercial power whereas the fusion communities $5 billion pet project ITER will only provide thermal energy (Smith, 2003). "Solar power satellites currently represent the only real long-term alternative to fusion reactors and should deserve a similar attention" (Ruth & Westphal, 1980).

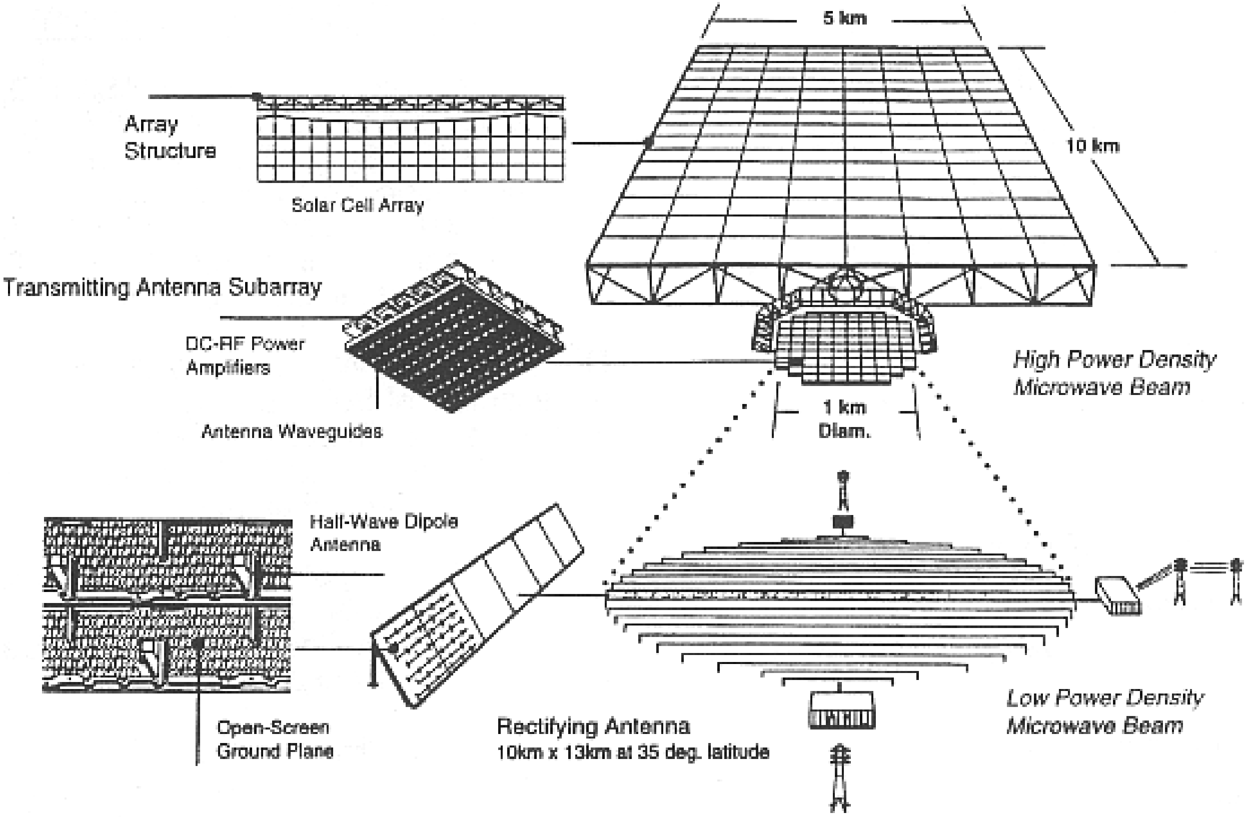
2.1.0 Satellite

There are five main options for the choice of space-based platform, or satellite, for an XPS system differentiated by the orbits of these proposed systems. The five orbits; geosynchronous (GEO), low-earth orbit (LEO), elliptical, supersynchronous, and lunar; all have distinct advantages and disadvantages.

2.1.1 GEO

The classical, or reference, system proposed by Glaser operates in geosynchronous orbit. This has the advantages of placing the satellite in sunlight most of the time, and always above the same place on Earth thereby providing a dedicated power supply. The satellites themselves are similar in form to existing solar-powered satellites with much larger solar-cell arrays.

Figure. 2-1 Reference system

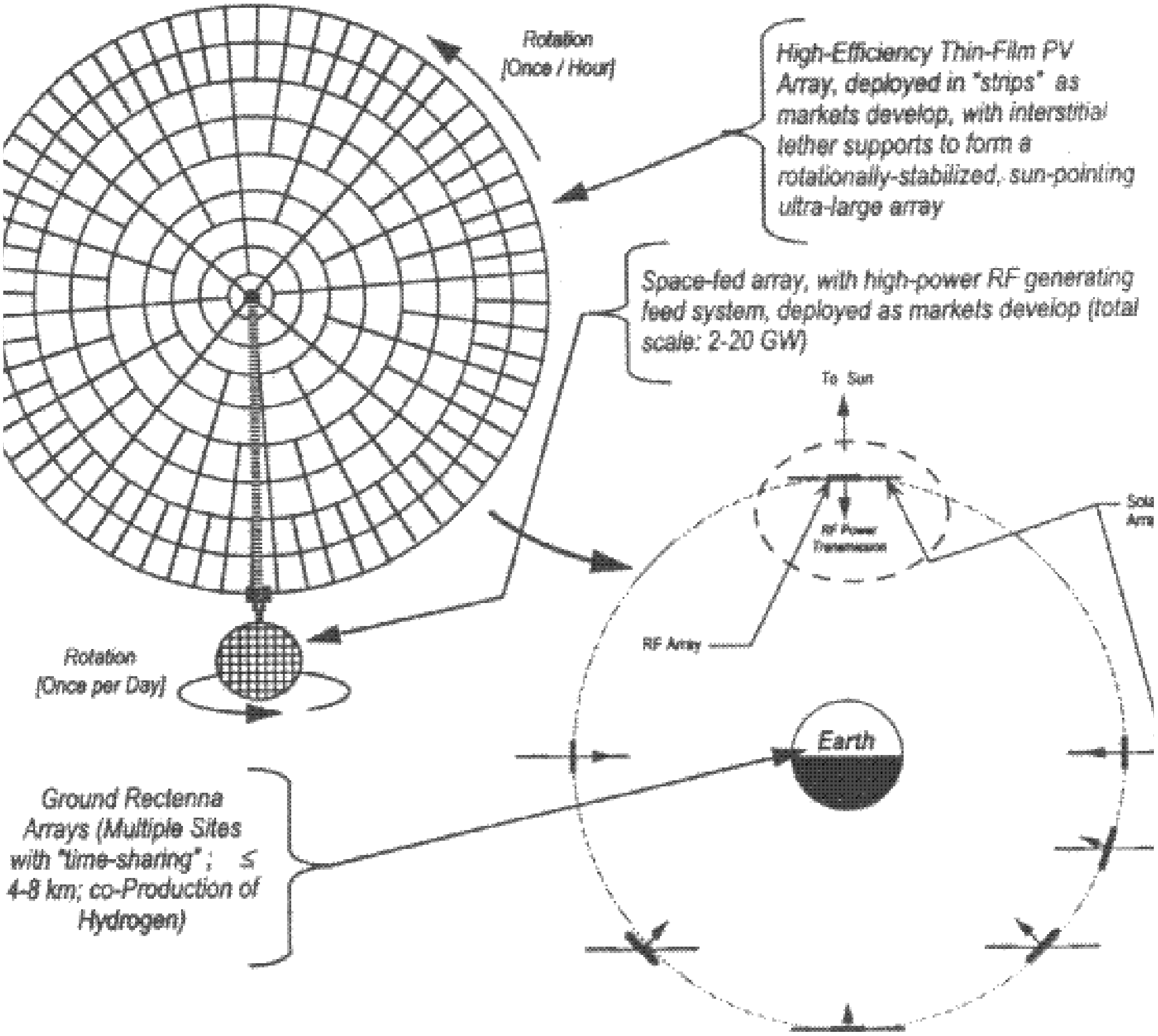


Note. From “A Fresh Look at Space Solar Power: New Architectures, Concepts and Technologies” by J. Mankins, 1997, National Aeronautics and Space Administration.

Figure 2-1 depicts a reference system and figure 2-2 a modern alternative, the SolarDisc from Mankins’ “Fresh Look”.

Major issues specific to geosynchronous satellites are orbit crowding due to competition for slots such as with telecommunication satellites, limitations on the range of serviceable latitudes from their equatorial vantage point, and to a lesser extent periodic occlusion by the Earth.

Figure. 2-2 SolarDisc

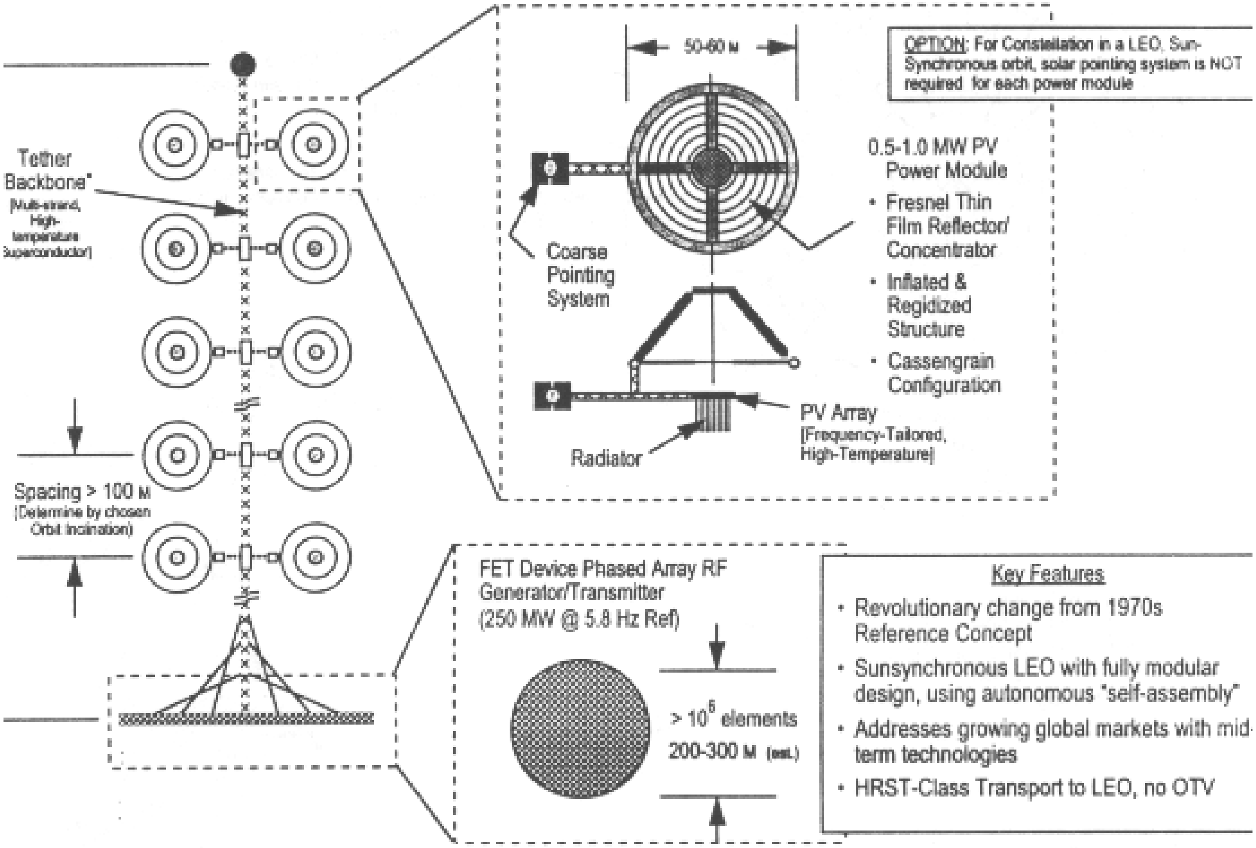


Note. From “A Fresh Look at Space Solar Power: New Architectures, Concepts and Technologies” by J. Mankins, 1997, National Aeronautics and Space Administration.

2.1.2 LEO and Elliptical

There are multiple proposals for low-earth orbit XPS satellites including the “Fresh Look” SunTower featured in figure 2-3 and the Mitsubishi SOLARBIRD concept. SOLARBIRD would be a fleet of small satellites each providing about a megawatt of power. The system is intended initially as a replacement for batteries in portable devices. Use of multiple small satellites provides redundancy and allows for the benefits of mass production. Unfortunately LEO satellites suffer from significant atmospheric drag, and a short period resulting in frequent disruption of service requiring a large number of satellites. To overcome this SunTower would be moved out of LEO into an elliptical orbit as it grows, where it could service high-latitudes (as opposed to GEO) and spend more time over a particular region

Figure. 2-3 SunTower

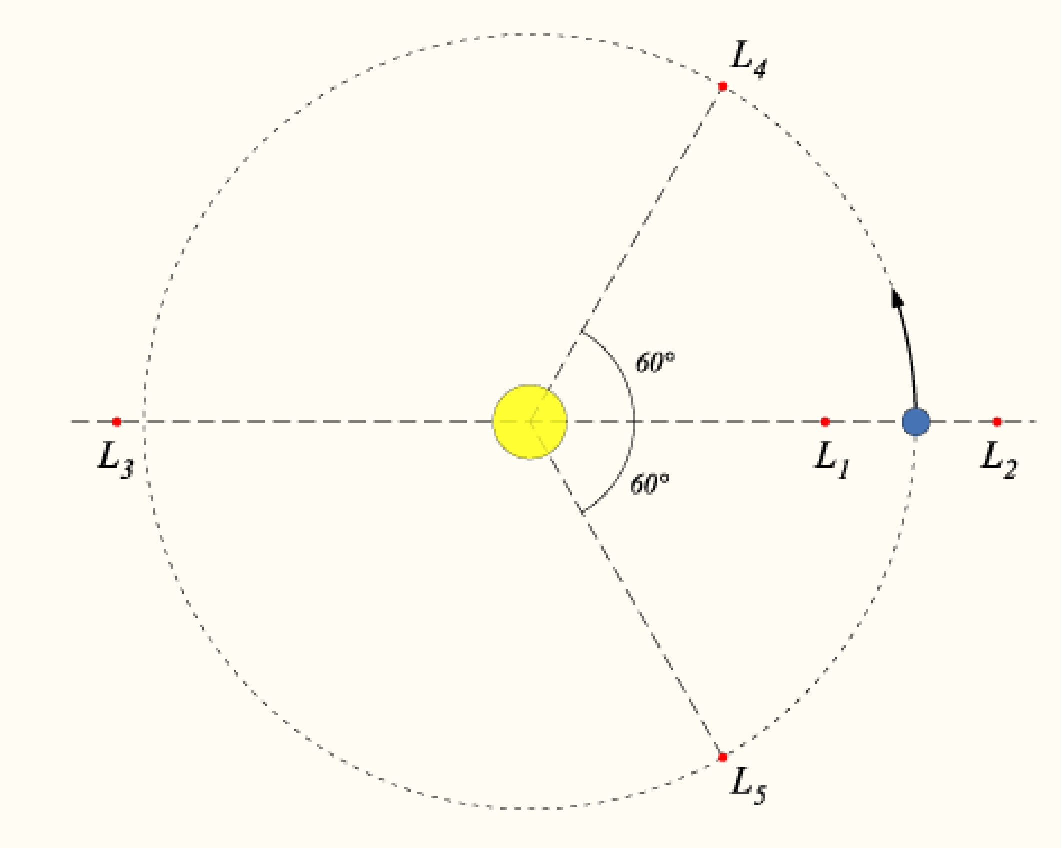


Note. From “A Fresh Look at Space Solar Power: New Architectures, Concepts and Technologies” by J. Mankins, 1997, National Aeronautics and Space Administration.

2.1.3 Supersynchronous Orbit

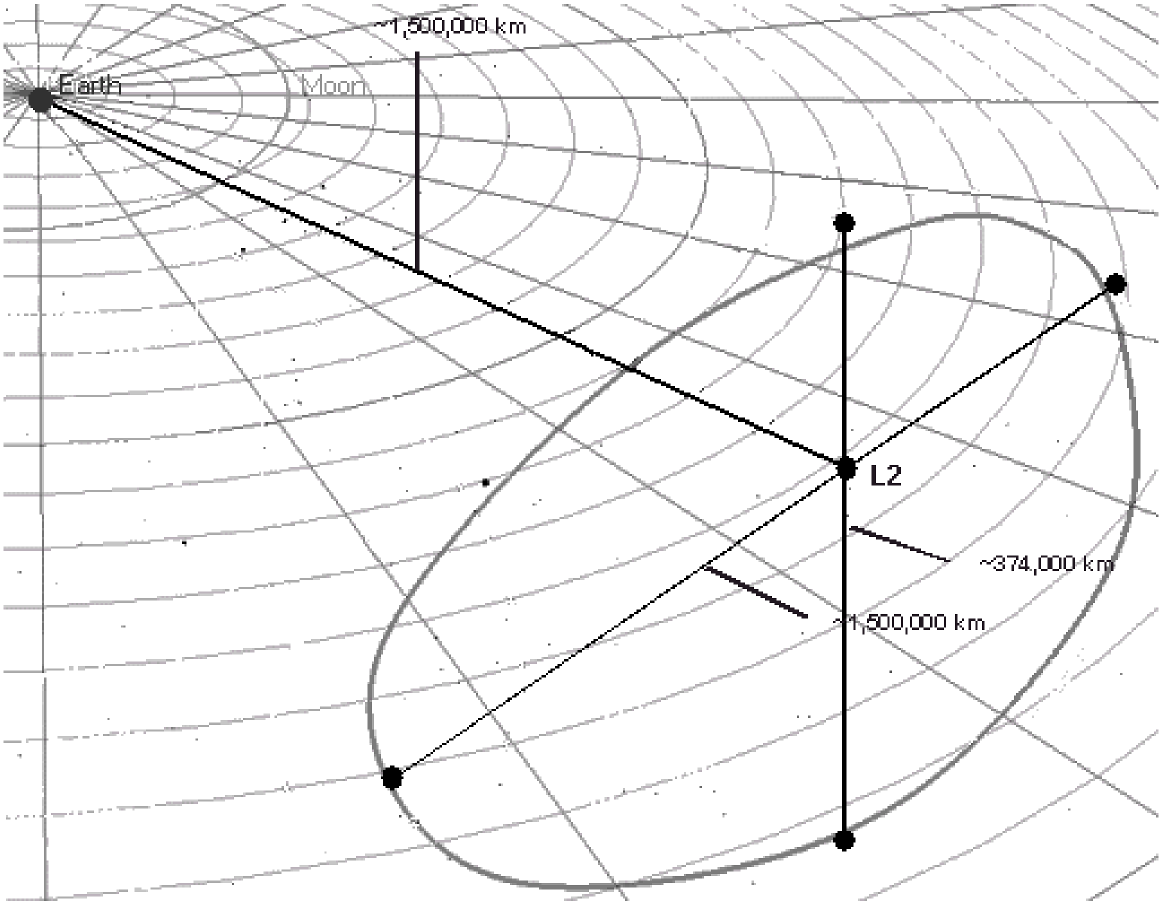
In 1997 Geoffrey Landis proposed a “supersynchronous” XPS satellite. The supersynchronous satellite orbits the L2 point to overcome the meta-stability of this position caused by the moon and other celestial bodies. Such a satellite would posses numerous interesting features. The XPS would nearly always be in sunlight, and yet it would be on the dark side of the planet! Every other XPS orbit proposed suffers from its own diurnal cycle preventing them from providing baseload power, exactly what a supersynchronous satellite can do. L2 halo satellites may also reduce design requirements thereby reducing costs. For certain setups the XPS might use the same dish for transmission and receiving. The position of the satellite does not require an expensive joint between the transmitter and array usually necessary in other designs to keep the array properly oriented to the sun (Landis, 1997).

Figure. 2-4 Sun-Earth LaGrange points



Note. From *Lagrange points* by FreeDictionary.com, 2004, [WWW document]. URL http://encyclopedia.thefreedictionary.com/Lagrange%20points. Copyright 2004 Farlex, Inc.

Figure. 2-5 Sun-Earth L2 Halo Orbit

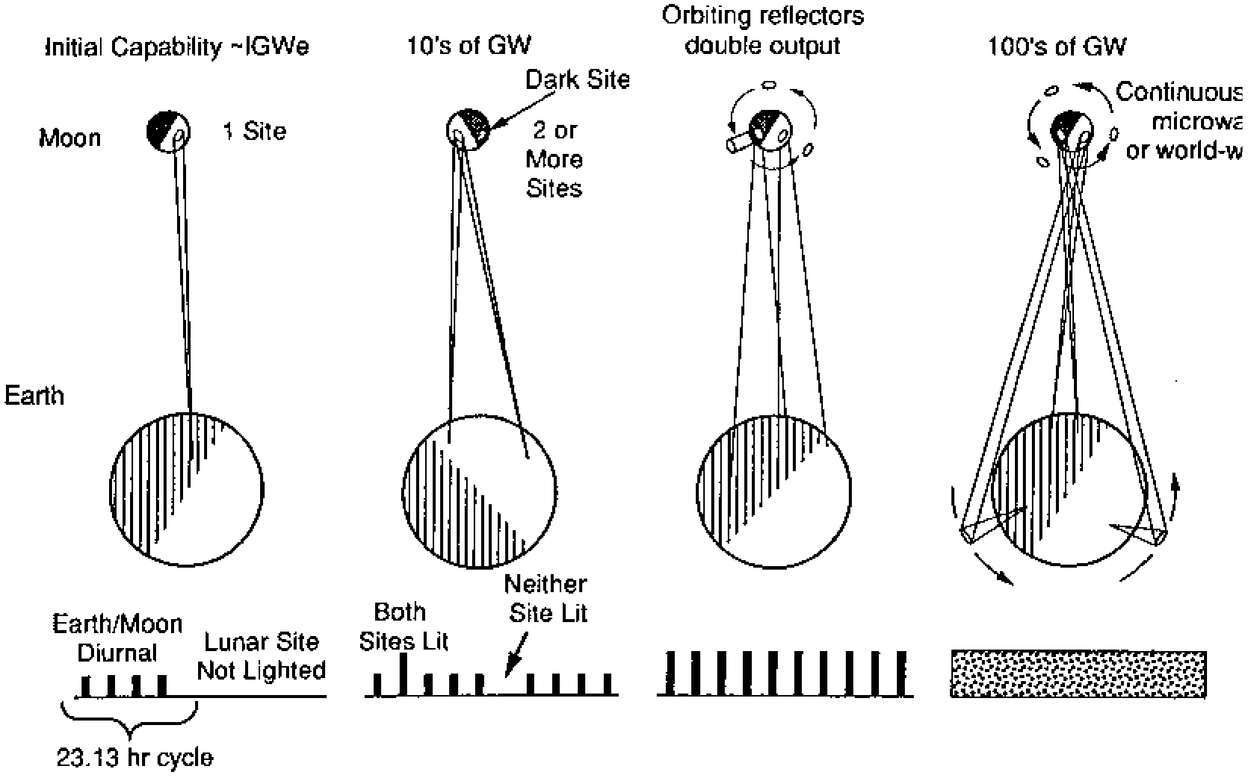


Note. Adapted from *Proposed Orbit for JWS* by E. Smith and S. Campion, 2004, [WWW document]. URL http://ngst.gsfc.nasa.gov/project/text/orbits.html National Aeronautics and Space Administration

2.2.0 Lunar

Due to the size of most XPS system concepts providing a stable platform is rather difficult. Criswell has advocated the use of the earth's moon as the platform for XPS deployment. While the moon has an extended day night cycle (figure 2-6) this can be overcome to harness the 13 exawatts of solar power it receives (Criswell, 2002). The moon's orbit is also comparatively free of debris.

Figure. 2-6 Lunar installation power cycle



Note. From Transportation and Operational Aspects of Space Energy systems" by Woodcock, 1989, National Aeronautics and Space Administration

2.3.0 Summary

Figure. 2-7 Orbit Comparison

Location	Scale**	Distance (km)*	Dispatch time(s)
LEO	1-100 MW	<1,500	0.01
Geosynchronous	2-20 GW	36,000	0.24
Supersynchronous		1,500,000	10.01
Lunar	20TW	384,000	2.56

** Scale of proposed systems. *Dispatch time is taken as time to signal, or 2d/c (Mankins, 1997. Mitsubishi, 2003. Criswell, 2002)

All orbits will have place satellites out of direct sunlight some fraction of the period, however the fraction diminishes for higher orbits. A supersynchronous satellite will be eclipsed for approximately 5% of the time (Landis, 1987).

3.1.0 Solar Conversion

There are many mechanisms for the conversion of sunlight into electrical energy and most will work for satellites or lunar XPS systems however some are better suited to lunar installation due to mass and temperature differential constraints. There are also a few “exotic” or more experimental conversion cycles possible including the photon engine and optical rectenna which do not yet warrant detailed discussion.

3.2.0 Photovoltaics (PV)

Most XPS analyses follow Glaser’s lead and use a PV system to capture solar energy. PV systems vary in efficiency from 5% for amorphous Si to 30% for GaAs however GaAs is considerably more expensive than amorphous or crystalline silicon (with an intermediate efficiency). It is possible to make better use of a high-efficiency cell by switching from a planar array to concentrators in combination with the photovoltaic cells. This allows for the use of smaller high-cost, (comparatively) high-efficiency GaAs cells which is then offset by the supporting concentrator infrastructures increased flux (Marniak & Tillotson).

Recent developments at Lawerence Berkeley National Laboratory by Wladek Walikiewicz and Kin Man Yu have led to the discovery of two potentially ground-breaking PV materials. InGaN, has a band-gap proportional to the concentration of Indium, and one therefore ought to be able to create a multi-junction cell that captures a broader portion of the EM spectrum. A more recent discovery, ZnMnTe is a multi-gap material giving it a theoretical efficiency of greater than 50% (Preuss, 2004). There is also interest in the potential to create organic photovoltaic substances (Glaser, 1968).

3.3.0 Mechanical

There are several mechanical or so-called “dynamic” conversion cycles available including Brayton and Stirling. Mechanical heat conversion cycles have a demonstrated efficiency of 42-56% (Price, 2000). Unfortunately, unlike solid-state systems, lubrication is a concern. Also, mechanical systems are typically four times the mass and ten times the cost per watt of PV (NRC, 2001). This and the limitation imposed by Carnot efficiency; one might use the dark-side of the moon as the radiator for T_c; would suggest the moon is the best site for mechanical systems.

4.1.0 Wireless Power Transmission (WPT)

Wireless power transmission is the keystone to XPS. In fact, it’s been suggested for use in harnessing distributed and far afield renewables as well (Glaser, 1993. Angelini, 1988). An XPS system would lock onto signal transmitted by a beacon at the receiver station on Earth and convey energy by transmitting high-power EMF. Conversion options for receiving stations on Earth are similar to those available for satellites and conventional solar systems however land use would be 1/10 to 1/100 that of terrestrial stations converting solar flux with comparable capacity (O’Neill, 1975).

4.2.0 Supply Smoothing -- Storage and Supplement

Figure 2-7 gives an approximation of the dispatchability of XPS solar however it masks a crucial point, solar flux is like run-of-the river hydro -- use it or lose it. Fortunately demand is generally cyclic and if instantaneous load information were transmitted with the beacon signal it would be possible to take advantage of some storage mechanisms available for XPS. Flywheels are particularly well suited for use in XPS systems as Landis points out because they can take advantage of the vacuum (1989). Thermal storage poses problems however, the requisite mass for a satellite is prohibitive and regolith conductivity prevents use of the moon as a heat sink.

4.3.0 Microwave Transmitter

Numerous microwave transmitter technologies are available including magnetrons, klystrons, and solid state amplifiers. The klystron and magnetron have similar efficiencies in the vicinity of 80% whereas RF solid state amplifiers(SSA) are still in development and their performance remains unclear (Maryniak & Tillotson, 1988. OTA, 1981). However, Each transmitter has different specific mass and composition characteristics which may be the final determinant. While SSA are expected to only operate under strict conditions they are predicted to have a much longer lifetime than either of the alternative vacuum tube based amplifiers (OTA, 1981).

The de facto frequency for a microwave transmission system is approximately 2.45 GHz. This choice minimizes atmospheric attenuation, largely due to water droplets, and is over 99% efficient. 5.8 GHz is 90% and is also considered a viable option as losses less than 15% are deemed acceptable (Welch, Davis & Cox, 1982.)

4.4.0 Laser Transmitter

Some laser systems are selected for by the choice of transmission frequency, and others such as closed-chemical cycle or solar pumped lasers which are less tunable may be selected against. The ability to tune the emissions frequency of some lasers, such as a free electron laser (FEL), allows the selection of a frequency for minimal atmospheric attenuation. There are potential mass production benefits in the use of FEL as they may be used as receivers as well (next section), doubling the quantity required for a complete XPS system. Preferred lasants for chemical lasers are CO or CO_2, which have a similar wavelength to the highly efficient electron discharge lasers (EDL). Beverly (1982a) recommends lasers in the 2, 9, and 11 µm ranges. However if 9 µm is chosen one must use a pure compound of minor isotopes, use of $^{12}C^{16}O_x$ (Beverly, 1982a) would interact with atmospheric concentrations of the same gas. In fact, use of a $^{12}C^{18}O$ laser increases transmission efficiency by 250% over $^{12}C^{16}O$ (Walbridge, 1982).

A laser XPS system is scalable in small quanta, whereas a microwave system must be deployed full scale because of economic and transmission issues (Walbridge, 1982). This allows for progressive experimentation and deployment. Lasers are also coherent and therefore less susceptible to spatial dispersion.

Laser transmission systems have several advantages over microwave systems, however notable drawbacks are their greater sensitivity to aerosols and weather conditions as well as 50% lower transmission efficiency (NRC, 2001). Weather and aerosol sensitivities can be mitigated by “hole boring” or beaming sufficient power densities to vaporize particles by heating from intentional absorption. This has been shown to be effective for 9 and 11 µm beams and requires negligible power (Beverly, 1982a).

4.5.0 Terrestrial Receiver

The final leg in WPT, as well as an XPS system is the Earth-bound receiver. Receiver technologies are largely the same as those available for solar conversion on satellites. Partially indicated by the transmission method. Mechanical or thermodynamic conversion cycles, used in traditional power generation are of course viable options.

4.5.1 Photovoltaics

It may be possible to select certain photovoltaic materials in order to match-up the incoming radiation with the work-function, or band-gap of the material to optimize conversion efficiency. An advantage of photovoltaic receivers, though not inherently unique to them, is there ability to function without XPS transmitter input (Landis, 1997). This provides a backstop baseload, it is also why Landis argues that XPS and terrestrial PV are not competitors, but rather XPS is an evolutionary step beyond the former to supplement supply.

For more information about photovoltaics technologies, impacts and potentials see chapter 13 of Sustainable Energy: Choosing Among Options (Peters, Drake, Driscoll, Golay & Tester, 2004), especially sections 13.5-13.7.

4.5.2 Rectenna

Rectifying antennas are webs of diodes and antennae constructed on the scale of the wavelength of the light to be received and can be used to convert EMF to direct current at efficiencies of 85%. It is interesting to note that rectenna conversion yields approximately 10% thermal waste vs. 150% and 250% for coal and nuclear. (O’Neill, 1992).

Rectenna are traditionally used for longer wavelength radiation such as microwaves though it may be possible to create so called optical rectenna.

5.1.0 Issues

As with many complex system there are many complicating factors and trade-offs to balance when choosing an XPS system. Because the system components are tightly bound, this inter-connected relationship carries over to the resulting policy options and systems design choices as well.

5.2.0 Atmosphere Interactions

Some losses in transmission are proportional to transmission distance, or orbit radius, resulting in greater beam spread. Shorter radius orbits must transmit at larger angles than distant satellites to reach middle to high latitudes. These larger angles equate to a longer atmospheric transmission path and increased attenuation.

High-density microwave power transmission would result in significant perturbations of the ionosphere and possible interference with telecommunications and other EMF. This can be avoided by limiting microwave density to 23 mW/cm2, which means the reference 5 GW system would require a 5 km^2 receiver (Duncan, 1981).

5.3.0 Politics

There are numerous political, particularly international, concerns about XPS systems not the least of which is weaponization. It is facile to imagine the use of “high power” beams from space to military ends, and to dissuade others of the impracticality of XPS as a weapons platform is difficult. There also aesthetic concerns about the deployment of large satellites in orbit or on the moon. Other areas requiring diplomatic efforts are orbit and spectrum allocations. GEO slots are valuable and in competition with other satellite functions. Many of the proposed bands for laser and microwave transmission have been previously allocated (Logsdon, 1981. Diederiks, 1981). Finally, while the matter of investment in power infrastructure is a national policy issue related to security and trade-offs the sheer scale of XPS may require collaboration and joint venture (Logsdon, 1981). Complicating the matter of investment, particularly commercial, are traditions and treaties classifying space as shared global heritage (Diederiks, 1981).

5.4.0 Economics

Like many renewable energy sources, strictly speaking, there are no fuel costs associated with XPS. However to simplify cost calculations, one might wish consider the costs of consumables for humans in space as fuel costs. Maintenance costs of XPS depends upon the selections made from all options and initial investment in R&D and capital. For instance, according to Duncan the receiving rectenna is 42% of cost of a microwave-based WPT XPS system (1981). Gallium arsenide cells are more expensive than silicon cells however they are more efficient and they are believed to be three times harder to radiation (Marniak & Tillotson, 1988). Radiation hardening vs. refurbishing (re-annealing) of cells is a major trade-off between XPS maintenance costs and R&D and capital investment.

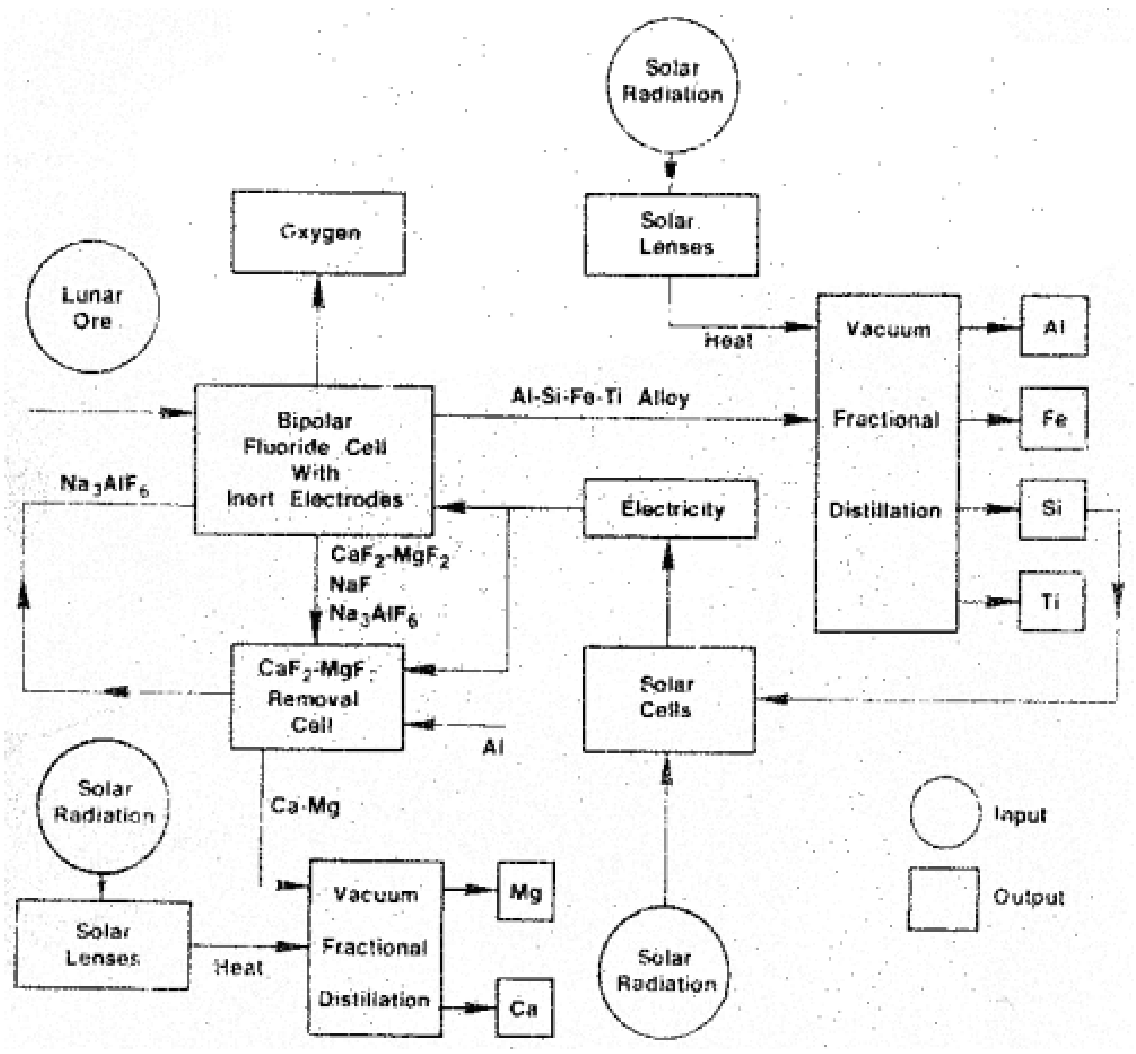
There are numerous views concerning the economics of XPS ranging from those who deem it fiscally implausible if not impossible to this whom would characterize XPS as an economic imperative. The economic feasibility of XPS is dependent upon the assumptions made. Fetter (2004) outlines a laundry list of conditions which all must be met for an economically viable system in his eyes. He makes implicit assumptions in many of these such as the use of no lunar material, see section 5.4.1. This assumption has a major impact on his analysis because his requirement that the specific power of the system is less than 200 W/kg, would appear to be achievable. Landis outlines a conservative estimate for a thin-film system of 220 W/kg for cells constructed from lunar mass (1999).

Heiss argues that traditional economic measures of projects may not be applicable to XPS. “Non-Archimedian” systems, where a finite set of existing capabilities cannot provide the capabilities of the system, should proceed through R&D because there is no other was to purchase this information. “There is no other long-term, feasible, economic energy options ... that have *been proven in principle* to provide most if not all of mankind’s energy needs.” Additionally, Heiss views XPS as an insurance policy against future high prices of energy sources; if XPS is not deemed “economical” now it places a cap on future prices which is especially important if the margin between XPS and other systems is narrow (1981).

5.4.1 Mass

A major cost in XPS deployment is the ferrying of system components to orbit. Proposed XPS concepts require a mass transfer rate several orders of magnitude larger than the current capabilities of the United States and Russia combined (Criswell, 2002). Traditional launch costs is prohibitively expensive (Fetter, 2004). Perhaps more disconcerting existing propellants for heavy lift launch vehicles.have been shown to have significant and relatively long-lived depletion effects on the ionosphere which some theorize this could lead to climate mod (Duncan, 1981). A possible solution to these problems is the use of lunar materials for XPS manufacture in situ, regardless of the platform or orbit selection. The composition of the moon is largely similar to the Earth and rich in metals and metalloids useful for XPS. Furthermore, Landis calculates that it is possible to launch nine times the mass to GEO from the moon for same thrust than from Earth (1999). However, “[w]e should not underestimate the development efforts that will be required to construct, launch, and operate” an XPS system (Glaser, 1968). Lack of lunar carbon and halogens or other reducing agents as well as acids and bases imposes some limits on the percentage of systems material derivable form lunar mass. however figure 5-1 but demonstrates a material extraction cycle with recoverable reagents (Jarrett, Das & Haupin, 1980).

Figure. 5-1



Note. From “Extraction of Oxygen and Metals from Lunar Ores“ by N. Jarrett, S. K. Das, and E. Haupin, 1980, Space Solar Power Review, 1,(4), p. 283. Copyright 1980 by the SUNSAT Energy Council.

5.4.2 System Efficiency

System efficiency is dependent upon component choice and is most strongly influenced by the lossy similar steps of sunlight conversion and WPT reception. Glaser suggests efficiency improvements may be possible through new PV materials development, particularly organics, however the lack of volatiles on the moon limits the potential to pursue deployment of any developed material. (Jarrett et al, 1980). A promising theoretical device termed a photoklystron could potentially serve as both solar energy converter and microwave transmitter with 50% efficiency (OTA, 1981. Jones, 2000).

5.5.0 Environmental Impacts

There is general concern about wildlife impacts, particularly on avian and insect life traversing the power beam, but also about the land use and the footprint of an XPS system. Beverly finds no significant environmental impacts specific to laser transmission at the proposed frequencies other than this concern for flying lifeforms (1980).

5.5.1 Health & Safety

Despite the classification of the proposed transmission frequencies as non-ionizing radiation there are concerns about possible health impacts, as there are with cellular phones and long-term exposure to other EMF fields.

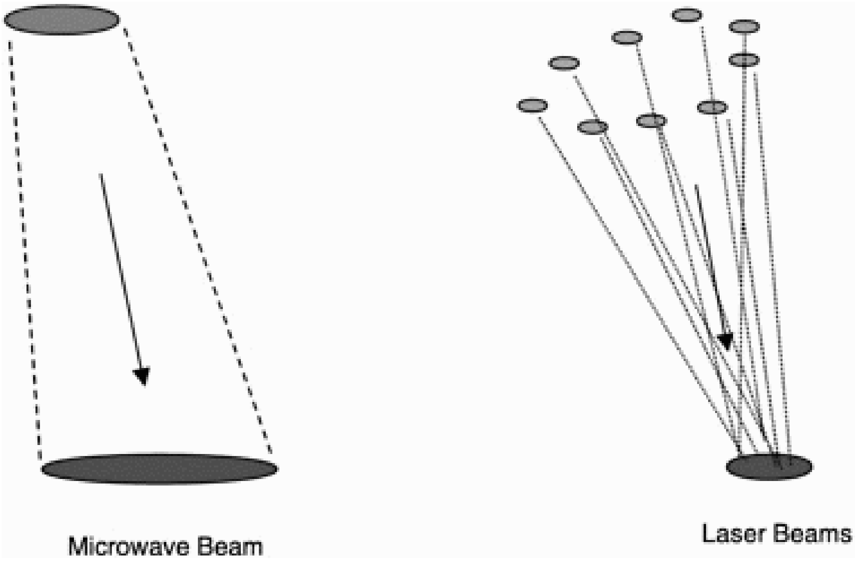
5.5.2 Energy Balance

XPS provides “new net energy” to the Earth if a high-orbit satellite such as lunar or supersynchronous system is used. Criswell argues that this energy is decoupled from the biosphere, unlike terrestrial solar power which must displace ecological functions, and therefore can allow for environmentally friendly economic development (2002). However there is evidence that as little as a 1% increase in atmospheric absorption may have significant climatic consequences (Beverly, 1980).

5.5.3 Land Usage

XPS systems encounter many of the same issues as terrestrial PV, though on a smaller scale. A lunar XPS system could deliver 20 TW_e with 100,000 km^2 of microwave rectenna receivers. This is less than the combined area, including mines etc., of the existing thermal and electric systems which deliver 14 TW_t or 4.7 TW_e and is also 5% of area required for the same power capacity using a traditional PV system (Criswell, 2002).

Figure. 5-2 Qualitative Microwave vs. Laser Land Use



Note. From Laying the Foundation for Space Solar Power: An Assessment of NASA's Space Solar Power Investment Strategy (p. 74) by National Research Council, 1991, Washintgon, D.C.: National Academy Press. Copyright 2001 National Academy of Sciences.

Citing concerns for microwave receivers are significant. ”It is not possible to reduce the microwave reception area by simply reducing the total energy received because this area is governed directly by simply reducing the transmitted distance and inversely by the transmission dish size or the radiated frequency” (Franklin, 1981). Criswell proposes the clever solution of placing rectennas over existing energy infrastructure land-mass such as strip mines (Criswell, 2002). Offshore rectennas are an option, however they will have a “very high capital cost and a significant impact on shipping lanes” (Franklin, 1981). Itoh & Ogawa (1988) propose a planned city under a suspended rectenna, it may be difficult to assuage fears of radiation enough for such a plan to viable.

Laser transmission systems fare even better than microwaves and use only 5% of the area required for microwave transmission, or 0.25% of a conventional system (Walbridge, 1982). Laser siting is also more flexible than microwave siting. The scale of the space requirements makes the system topologically less restrictive, large open level plains are not necessary and laser reception sites may be nestled amongst load centers. This is especially significant for Europe where there is little remaining free space of adequate extent for microwave receivers and what does exist is not near load centers, though they are comparatively closer than in the U.S. (Beverely, 1982b).

6.1.0 Conclusions

There are a wide variety of conceptual studies on XPS but most are on single systems with little leeway for deviation from the authors' assumptions and from these sweeping judgements about the entire concept are made. For instance Kerwin and Arndt (1985), deem lunar XPS systems impractical though they only investigate a microwave transmission system without the incorporation of any lunar material in the design. There are sufficient options for XPS that a practical system seems possible. Furthermore, one must remain open to the potential for evolutionary and synergistic systems such as use of research systems for commercial power or XPS combined with terrestrial PV.

Further Resources

- Power From the Sun, http://www.powerfromthesun.net/
- SSP Monitor, http://www.wronkiewicz.net/ssp/

References

Angelini, A. M. (1988). On the Possibility of Intercontinental Power Transmission via Satellite. Space Power, 7, 175-186.

Beverly III, R. E. (1980). Laser-SPS Systems Analysis and Environmental Impact Assessment. Space Solar Power Review, 317-344.

Beverly III, R. E. (1982a). Meteorlogical Effects on Laser Propagation for Power Transmission. Space Solar Power Review, 9-29.

Beverly III, R. E. (1982b). Power Availability at Terrestrial Receptor Sites for Laser-Power Transmission from the Satellite Power System. Space Solar Power Review, 31-44.

Criswell, D. R., (2002). Solar Power via the Moon. The Industrial Physicist. pp. 12-15.

Diederiks-Verschoor, I. H. PH. (1981). Remarks on Some Legal Aspects of Solar Satellites - An Overview. Space Solar Power Review, 2, 143-149.

Duncan, L. M. (1981). SPS Environmental Effects on the Upper Atmosphere. Space Solar Power Review, 2, 87-101.

Fetter, S. (2004, January). Space Solar Power: An Idea Whose Time Will Never Come?. Physics and Society, 33. 1.

Franklin, I. V. (1981). Some Critical Aspects of Solar Power Satellite Technology. Space Solar Power Review, 2, 53-60.

FreeDictionary.com, (2004, January 31). [WWW document]. URL http://encyclopedia.thefreedictionary.com/Lagrange%20points

Glaser, P. (1968, November 22). Power from the Sun: Its Future. Science, 162, 857-861.

Glaser, P. (1993). Japan - The 21st Century's Global Energy Supplier?. Journal of Practical Applications in Space.

Heiss, K. P. (1981). SPS: An Economic Outlook. Space Solar Power Review, 2, 61-70.

Itoh, K., Ogawa, Y. (1988). Considerations on an Inland Rectenna. Space Power, 7, 211-216.

Jones, D. (2000, April 6). Daedalus: The sharper image. Nature, 404, p. 561.

Kerwin, E. M., Arndt, C. D. (1985). Cost Comparisons of Solar Power Satellites Versus Lunar Based Power systems. Space Solar Power Review, 5, 39-52.

Landis, G. (1989). Solar Power for the Lunar Night. 9th Biennial SSI/Princeton Conference on Space Manufacturing.

Landis, G. (1997, August). A Supersynchronous Solar Power Satellite. Proceedings SPS '97 Conference. Montreal: Canadian Aeronautics and Space Institute.

Landis, G. (1999, August 13). *Artemis Project: Lunar Production of Solar Cells* [WWW document]. URL http://www.asi.org/adb/02/08/solar-cell-production.html

Lodgson, J. M. (1981). International Dimensions of Solar Power Satellites: Collaboration or Competition?. Space Solar Power Review, 2, 109-113.

Mankins. J. (1997). A Fresh Look at Space Solar Power Architectures, Concepts and Technologies. 38th International Astronautical Federation.

Maryniak, G. E., Tillotson. B. (1988). Design of a Solar Power Satellite for Construction from Lunar Materials. Space Power, 7, 27-36.

Mitsubishi. (2003, September 25). SOLARBIRD. [WWW document]. URL http://global.mitsubishielectric.com/bu/space/topics/solar/sol01_b.html

National Research Council. (2001). Laying the Foundation for Space Solar Power: An Assessment of NASA's Space Solar Power Investment Strategy (pp. 36, 40, 74). Washington, DC: National Academy Press.

Office of Technology Assessment. (1981, August). Solar Power Satellites. Washington, DC: U.S. Government Printing Office

O'Neill, G. K. (1992, January/February). The World's Energy Future Belongs in Orbit. Trilogy

Preuss, P. (2004, March 24). *A Step Closer to the Optimum Solar Cell*. [WWW document]. URL http://www.lbl.gov/Science-Articles/Archive/sb-MSD-multibandsolar-panels.html

Price, S. (2000, December). Solar Power from Space. [WWW document]. URL http://firstscience.com/site/articles/solar.asp

Ruth, J., Westphal, W. (1980). Solar Power Satellites for Europe. Space Solar Power Review, 1, 351-360.

Silber, K. (2002, May 30). Serious Solar Power. [WWW document]. URL http://www.techcentralstation.com/053002B.html

Smith, A. (2003, August 11). The case for Space Based Solar Power Development. [WWW document]. URL http://www.spacedaily.com/news/ssp-03b.html

Smith, E. Campion, E. (2004, January 5). JWST Project: Proposed Orbit for JWST [WWW document]. URL http://ngst.gsfc.nasa.gov/project/text/orbits.html

Walbridge, E. W. (1982). Laser Satellite Power Systems: Concepts and Issues. Space Solar Power Review, 3, 45-71.

Welch, R. M., Davis, J. M., Cox, S. K. (1982). Transmission of Microwave Beamed-Power from an Orbiting Space Station to the Ground. Space Solar Power Review, 3, 99-119.

Woodcock, G. R., (1989), "Transportation and Operational Aspects of Space Energy systems", Report of NASA Lunar Energy Enterprise Case Study Task Force: NASA Technical Memorandum 101652 p. 97