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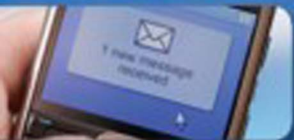

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Space Solar Power

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Abstract

The accelerating global consumption of affordable and available energy sources will soon present fundamental challenges. The need for new energy is driven by three factors: (1) growing global demand for energy to feed economic growth, (2) growing concerns regarding the long-term accumulation in Earth's atmosphere of fossil fuel-derived greenhouse gases, and (3) the prospect that during the coming decade's global production of petroleum (and possibly other fossil fuels) will peak and begin to decline. A wide variety of aerospace technologies – including photovoltaic arrays, fuel cells, and wind turbines – have already been applied in conventional renewable energy systems. However, although already- existing "green" technologies can make a substantial contribution to the long-term energy challenge, these technologies are unlikely to provide the huge amounts of new and sustainable energy that will be needed in the coming decades.

As a result of the above factors, various new technologies now are being researched. One of the most promising and technically challenging of these is "space solar power" (SSP): the concept of collecting the virtually limitless energy of the sun available in space and delivering it safely and cost-effectively to communities on Earth.

Key Words: energy, space solar power,

Introduction:

The solar energy available in space is literally billions of times greater than we use today. The lifetime of the sun is an estimated 4-5 billion years, making space solar power a truly long-term energy solution. As Earth receives only one part in 2.3 billion of the Sun's output, space solar power is by far the largest potential energy source available, dwarfing all others combined. Solar energy is routinely used on nearly all spacecraft today. This technology on a larger scale, can supply nearly all the electrical needs of our planet.

Electricity generation using photo-voltaic cells is receiving increasing attention as a means of electricity generation that produces neither CO2, NOx nor SOx pollution as do systems using fossil fuel burning, nor radiation like nuclear power systems. However, because solar energy generation is impossible at night and of poor efficiency during cloudy weather, stable electricity generation is difficult.

However, if solar panels are launched into space they can produce power continuously, independent of the weather and of the day-and-night cycle. The Solar Power Satellite (SPS) concept involves a satellite carrying photo- voltaic panels in geo-stationary orbit (GEO) to generate electricity, and transmitting this power to the Earth's surface. Solar power generation, especially space solar power, is one of the most promising alternative technologies for reducing CO_2 emissions and thus reducing "Green House Effect".

Space based Solar power is a challenging long term opportunity to tap the unlimited resources of the space rather than to rely on Earth's limited ones. Space has a number of advantages for solar power. For one, a satellite high in a geosynchronous orbit (35,887 km altitude) is rarely shaded by the Earth. As a result, it is in sunlight for about 98% of the time. Also, there is no atmosphere or clouds to attenuate or diffuse the incoming solar radiation.

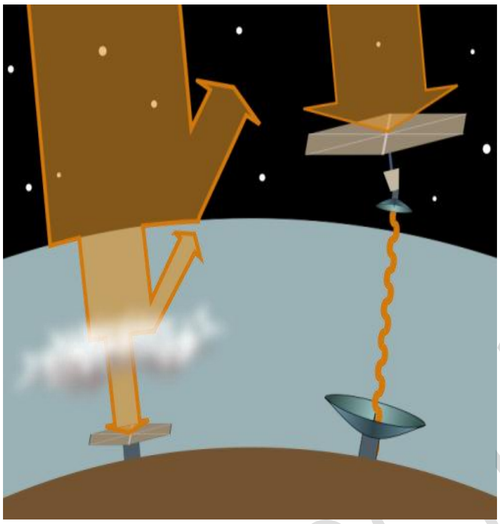

Fig. 1. Solar energy losses

Left: Part of the solar energy is lost on its way through the atmosphere by the effects of reflection and absorption.

Right: Space-based solar power systems convert sunlight to microwaves outside the atmosphere, avoiding these losses, and the downtime (and cosine losses, for fixed flat-plate collectors) due to the Earth's rotation.

The successful implementation, management and optimization of solar power conversion to D.C. electric power, transformation/conversion of generated power to suitable form for transmission to earth, conversion of received power to power-frequency, and inter-connection to terrestrial power systems still pose challenges not fully resolved technically, socially, economically and politically.

Design Concept

The Solar Power Satellite or "Space Solar Power" (SPS) is a concept to collect solar power in space, and then transport it to the surface of the Earth by microwave (or possibly laser) beam, where it is converted into electrical power for terrestrial use. The recent prominence of possible climate change due to the "greenhouse effect" from burning of fossil fuels has again brought alternative energy sources to public attention. It is important to design the system to service the real-world electrical power market, not to an unreal average-price model. The following criteria will have to be used for a credible analysis of solar power satellite economic benefits and rate of return:

- Satellite power generation should fit electrical demand profile
- Satellite Power generation should generate power at the maximum selling price
- Use actual data on electrical demand & price.

The SPS is a gigantic satellite designed as an electric power plant orbiting in the Geostationary Earth Orbit (GEO). It consists of mainly three segments; solar energy collector to convert the solar energy into DC (direct current) electricity, DC-to-microwave converter, and large antenna array to beam down the microwave power to the ground. The first solar collector can be either photovoltaic cells or solar thermal turbine. The second DC-to-microwave converter of the SPS can be either microwave tube system and/or semiconductor system. It may be their combination. The third segment is a gigantic antenna array known as rectenna.

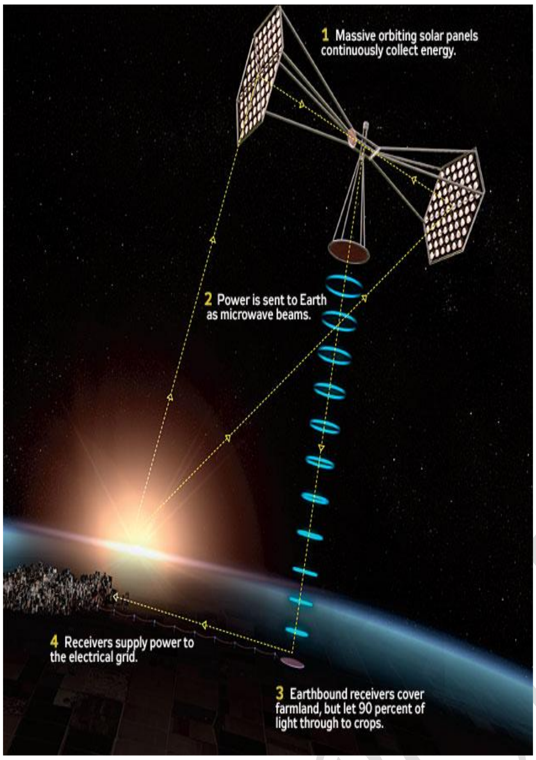

Fig.2. Conceptual outlook

The basic method of converting sunlight to electricity is known as photovoltaic (PV) conversion. Photovoltaic conversion uses semiconductor cells (e.g., silicon or gallium arsenide) to directly convert photons into electrical power via a quantum mechanical mechanism.

The space-based portion will not need to support itself against gravity (other than relatively weak tidal stresses). It needs no protection from terrestrial wind or weather, but will have to cope with space hazards such as micro meteors and solar flares.

The size of a solar power satellite would be dominated by four factors-

a. The size of the collecting apparatus (e.g. panels and mirrors)
b. The size of the transmitting antenna.
c. The distance from Earth to geostationary orbit (35,700 km),
d. The chosen wavelength of the microwaves.

For best efficiency, the satellite antenna should be circular and about 1 kilometre in diameter or larger; the ground antenna (rectenna) should be elliptical, 10 km wide, and a length that makes the rectenna appear circular from GEO (Geostationary Orbit). Smaller antennas would result in increased losses to diffraction/ side lobes.

Solar Collector

The energy received from the Sun in just one hour is sufficient enough to meet the entire global energy demand for around one year.

GEO Sun Tower: This architecture is similar to that of the MEO Sun Tower. However, it will have a geostationary Earth orbit (GEO) instead. The geostationary orbit allows a single satellite to supply power continuously to a given receiving station on Earth. This makes this architecture more versatile. Also, the total power will be greater due to the reduction in scanning loss. Due to the geostationary orbit, this structure will be deployed at a greater distance from earth, which will reduce encounters with space debris.

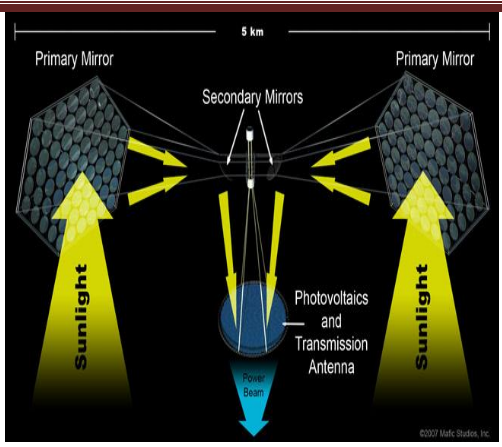

Fig.3. GEO Heliostat/concentrator

This architecture uses a geostationary orbit. This GEO Heliostat consisting of a mirror or system of mirrors that tracks the sun and reflects light onto a power generator/transmitter array. This architecture allows the Heliostat to be smaller and shorter than the Sun Tower architecture. This helps with power management and distribution.

Wireless Power Transmission

What allows Space Based Solar Power to be viable is increased, rapid advancement in wireless power transmission technology. There are two primary options for transferring power from the spacecraft to a receiver: microwave and laser. One key factor that must be considered to select the optimum technology is conversion efficiency (solar to microwave or laser, and microwave or laser to prime electrical power at the receiver). Another factor is the transmission losses due to attenuation, diffraction, scattering, etc.

Laser based technology is generally considered to be less viable for space based solar power because of the inefficient conversion from DC to laser to DC again. Also the absorption from the atmosphere makes laser based technology a poor choice.

The transmitted radiation would have to be non-ionizing to forbid probable ecological or biological impairment. The current technology trends dictate the possibility of using microwaves for the purpose. The D.C. power generated by solar cells assemblies would be suitably accumulated by appropriate series-parallel combination circuitry depending on the voltage and current level requirements to be fed to power conversion devices/systems to obtain microwave output power, at the required frequencies. The available option is to use either vacuum devices such as magnetrons, klystrons, cyclotrons, travelling wave tubes etc. or solid state devices like Gunn-sources, IMPATT diodes or microwave transistor oscillators.

The microwave technology consists of two parts: the transmitter and beam control. The transmitter takes the DC produced by the solar panels and beams it in the form of microwaves. The beam control accurately points the transmitter towards the receiver and adjusts the beam amplitude/ phase so that the system can transmit energy with high efficiency.

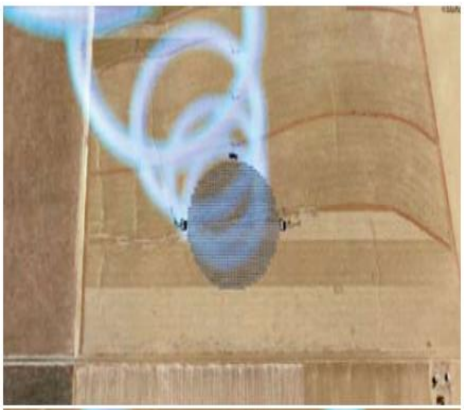

Fig.4. Microwave beams

Power transmission from the satellite to a rectenna is made by 2.45 GHz micro-wave beam emitted from the spacetenna, the antenna onboard the satellite, provided with retro-directive beam control capability. Using the principle similar to that of the U.S. Reference System, electrical and mechanical design of this system is simpler by employing a square shape and a single power level. This makes the microwave beam broad, and results in relatively inefficient power transmission and an increase in microwave exposure outside the rectenna. However in this case, the microwave power level is much lower than in the case of the Reference System, and well below international safety standards.

The beaming angle as large as 60 degrees of this case makes this requirement more important than in the case of the Reference System.

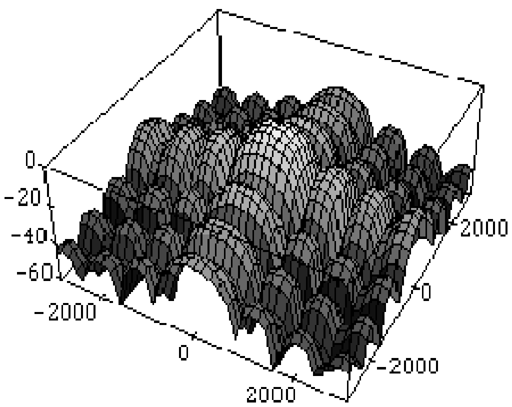

Fig.5. Microwave power distribution on ground Surface

Some draw backs of microwave technology is that the transmitter and receiver are much larger than that of laser based technology. However, microwave based technology can be converted much more efficiently and will experience less loss during transmission. It is also suggested that longer wavelength be used to decrease transmission loses.

Rectenna

Finally, the rectifying antenna (Rectenna) receives the microwave beams and converts it back to DC. The Earth-based rectenna would likely consist of many short dipole antennas connected via diodes. Microwaves broadcasts from the satellite would be received in the dipoles with about 85% efficiency. With a conventional microwave antenna, the reception efficiency is better, but its cost and complexity is also considerably greater. Rectenna would likely be multiple kilometres across.

Fig.6. Rectenna

With multitude of safety considerations, the only proposed approach to ensuring fail-safe microwave beams targeted to earth-antenna is to make use of retro-directive phased array antenna. A pilot microwave beam emanated from the centre of the rectenna on the ground procreates the phased front at the transmitting antenna. In turn, intelligent circuits in which all the antennas sub-arrays that compare the pilot beam's phase front with an internal clock phase to dynamically control the phase of the outgoing transmitted waves. This forces the transmitted beam to be centred precisely on the rectenna and to maintain a high degree of phase uniformity.

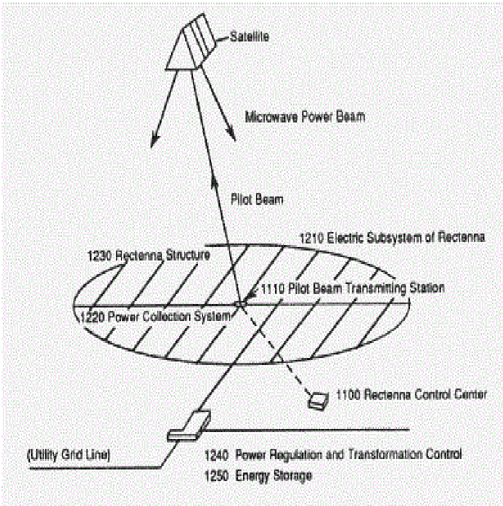

Fig.7. Retro Directive Phased Array Antenna

If, for any reason, the pilot beam is untraceable in time, the phase control system fails and the micro-wave power beam is automatically defocused. Such a system would maintain rapid decay process of micro-wave intensities outside of the rectenna keeping nearby populated areas completely unaffected.

Working

With the current status of foreseeable progress in technology, efficient wireless power transmission from power satellite to earth appears to be plausible either by microwave-radio or by lasers at optical frequencies. In either case, the transmitted radiation would have to be non-ionizing to forbid probable ecological or biological impairment. The current technology trends dictate the possibility of using microwaves for the purpose. The D.C. power generated by solar cells assemblies would be suitably accumulated by appropriate series-parallel combination circuitry depending on the voltage and current level requirements to be fed to power conversion devices/systems to obtain microwave output power, at the required frequencies. The available option is to use either vacuum devices such as magnetrons, klystrons, cyclotrons, travelling wave tubes etc. or solid state devices like Gunn-sources, IMPATT diodes or microwave transistor oscillators. The desired frequency, the conversion efficiency, the power capability and the power combining techniques are the major considerations in the choice of appropriate devices. Device level power-combiners can be more conveniently realized by integrated solid state systems. Circuit level combining may be implemented both with vacuum or solid state devices with equal ease. The radiation level combining is amenable with modern phased array antenna systems. In practice, a complex hybrid of all such techniques would have to be amalgamated ingeniously. Smaller is the wave-length smaller and more convenient is the size of the antenna. The angular beam-width of the transmitted wave is inversely proportional to the aperture of the antenna. However, atmospheric attenuation is one very important factor in deciding the optimum transmission frequencies. Accordingly, frequencies in the neighbourhood of the 2.45 GHz have been popularly proposed by the various technologists. The transmission system configuration has to incorporate all the provisions to take care of impedance matching, power reflections and device protections. A simple conceptual block diagram is depicted in Fig 8.

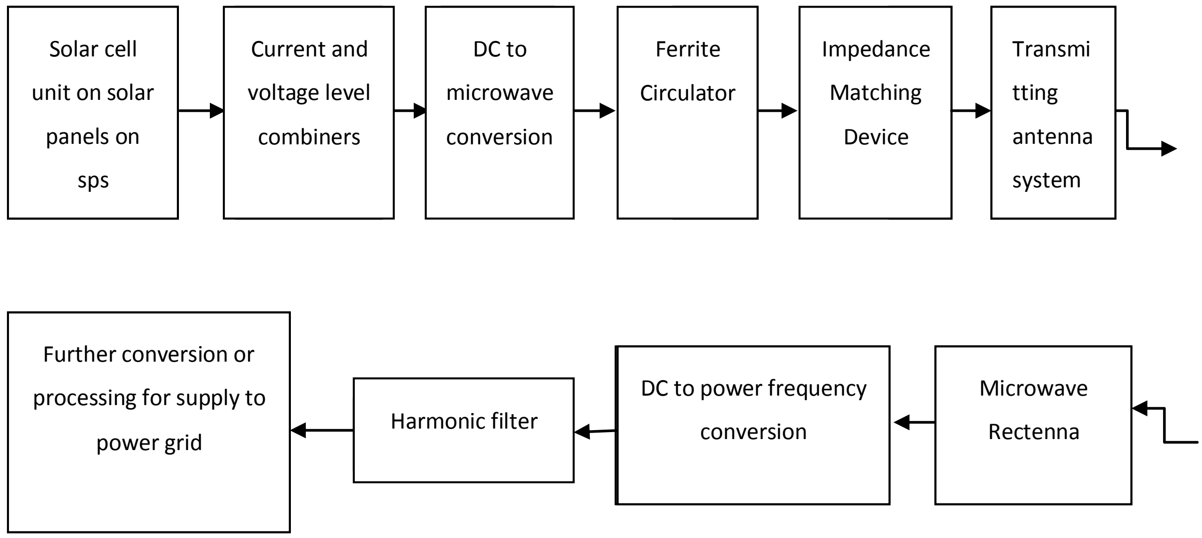

Fig. 8. Block diagram of proposed DC to power Frequency conversion wireless power transmission and reception

The transmitted microwave power after travelling through free space and earth's atmosphere is received and collected at ground location by a so named "rectenna" consisting of a large sized directional microwave receiving dipole-antenna combined with appropriate rectifying diode network, and harmonic filters, as shown in block diagrammatic form in Fig.8. The received and rectified D.C. power at ground would be further converted to 3 phase, 50 Hz power supply through controlled inverter systems so as to be fed to the terrestrial power-grid. The obtainable reconversion efficiencies are currently claimed to be 85%. The economics of such a power rectification and inversion sequence at the ground is currently unacceptable.

Merits of Space Based Solar Power

- Unlike oil, gas, ethanol, and coal plants, space solar power does not emit greenhouse gases.
- Unlike coal and nuclear plants, space solar power does not compete for or depend upon increasingly scarce fresh water resources.
- Unlike bio-ethanol or bio-diesel, space solar power does not compete for increasingly valuable farm land or depend on natural-gas-derived fertilizer. Food can continue to be a major export instead of a fuel provider.
- Unlike nuclear power plants, space solar power will not produce hazardous waste, which needs to be stored and guarded for hundreds of years.
- Unlike terrestrial solar and wind power plants, space solar power is available 24 hours a day, 7 days a week, in huge quantities. It works regardless of cloud cover, daylight, or wind speed.
- Unlike nuclear power plants, space solar power does not provide easy targets for terrorists.
- Unlike coal and nuclear fuels, space solar power does not require

environmentally problematic mining operations.

- Space solar power will provide true energy independence for the nations that develop it, eliminating a major source of national competition for limited Earth-based energy resources.
- Space solar power will not require dependence on unstable or hostile foreign oil providers to meet energy needs, enabling us to expend resources in other ways.
- Space solar power can be exported to virtually any place in the world, and its energy can be converted for local needs — such as manufacture of methanol for use in places like rural India where there are no electric power grids. Space solar power can also be used for desalination of sea water.
- Space solar power can take advantage of our current and historic investment in aerospace expertise to expand employment opportunities in solving the difficult problems of energy security and climate change.
- Space solar power can provide a market large enough to develop the low-cost space transportation system that is required for its deployment. This, in turn, will also bring the resources of the solar system within economic reach.

Current Challenges

Well focused and directed beaming of huge microwave power with only highly controlled beam-spread to a transmission distance of 36,000 kms needs elaborate design solutions incorporating intelligent feed-back systems. .

The operational safety of such a microwave based gigantically large system is also of legitimate concern both in terms of radiation hazards during operation as well as the probable dangers involved during a malfunction of the system.

The satisfactory technical performance and reliability of solar cells operating in the harsh space environment needs special and elaborate care in the choice of materials and system design. Radiation damage, high thermal stresses and unmatched spectral characteristics are some of the salient issues to be resolved optimally.

The development of micro-wave devices capable of handling continuous wave-power in the range of several hundred or thousand MW are still at the laboratory stage and need elaborate processing and design strategies for achieving the required goals.

To be economically competitive with other sources of electrical energy, the solar power satellite station would have to be extremely large. The current proposal suggests solar array of about 5 kms. x 10 kms in size feeding a 1 km. or more diameter phases array antenna to yield a power output of the order of 5000 MW. Such a space project appears formidable as on date in terms of cost, complexity and efforts.

Safety

Exposure to the beam is able to be minimized in other ways. On the ground, physical access is controllable (e.g., via fencing), and typical aircraft flying through the beam provide passengers with a protective metal shell (i.e., a Faraday Cage), which will intercept the microwaves. Other aircraft (balloons, ultra light, etc.) can avoid exposure by observing air flight control spaces, as is currently done for military and other controlled airspace.

In addition, a design constraint is that the microwave beam must not be so intense as to injure wildlife, particularly birds. Experiments with deliberate microwave irradiation at reasonable levels have failed to show negative effects even over multiple generations.

Some have suggested locating rectenna offshore, but this presents serious problems, including corrosion, mechanical stresses, and biological contamination.

A commonly proposed approach to ensuring fail-safe beam targeting is to use a retro-directive phased array antenna/ rectenna. A "pilot" microwave beam emitted from the centre of the rectenna on the ground establishes a phase front at the transmitting antenna. There, circuits in each of the antenna's sub-arrays compare the pilot beam's phase front with an internal clock phase to control the phase of the outgoing signal. This forces the transmitted beam to be centred precisely on the rectenna and to have a high degree of phase uniformity; if the pilot beam is lost for any reason (if the transmitting antenna is turned away from the rectenna, for example) the phase control value fails and the microwave power beam is automatically defocused. Such a system would be physically incapable of focusing its power beam anywhere that did not have a pilot beam transmitter.

Hazards due to launches

When hot rocket exhaust reacts with atmospheric nitrogen, it can form nitrogen compounds. These nitrogen compounds are problematic when they form in the stratosphere, as they can damage the ozone layer. However, the environmental effect of rocket launches is negligible compared to higher volume polluters, such as airplanes and automobiles.

Conclusion

The solar power satellite concept took birth on account of the fact that space possesses several attractive features over earth for harnessing the solar power. Some of these attributers are absence of atmosphere in space and abundance of solar radiation, which is unaffected by weather and day night cycles and hence illuminating the solar panels up to 98% of the time. The structure of SPS is considerably lighter due to the absence of gravity.

Successful realization and implementation of such power projects still necessitates a good amount of research, investigation and experimentation to make it economically viable.

The adaptation of the concept of solar power satellite appears more rewarding as it does not need any break-through in Science or Technology.

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