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SPACE BASED SOLAR POWER: CONCEPTS, DEVELOPMENTS AND CHALLENGES

Anice Alias

Abstract: ***To address the future energy needs of an expanding population there is a growing need to find clean reliable sources of energy. The world population is expected to grow to 8.9 billion by 2050. The world's energy demand is predicted to increase 44% by 2030. Currently, non-renewable resources such as oil, natural gas, and coal provide 85% of the world's energy. Ground-based solar, wind, hydropower, and other renewable energy options are currently in place, but provide less than 1 percent of the world's power. This percentage should grow but current renewable energy technology is limited and cannot provide enough power to match the growing need. Numerous scientists, engineers, and environmentalists have proposed space-based solar power as an alternative to traditional terrestrial photovoltaic collection.***

This paper focuses on one of the most promising other options; space based solar power (SBSP).

SBSP has the potential to fulfil the planets growing energy needs in the coming centuries. The concept of SBSP is simple. Satellites are sent into space fitted with solar panels that can convert the sun's rays into electricity. This electricity is then converted into microwaves and is then transmitted back to a receiver on the planet's surface. The receiver on the planet's surface converts the microwaves back into electricity where it can be fed into the power grid. Any company or country seeking to implement this technology faces certain legal and technical challenges. However the promise of SBSP is worth the cost of overcoming these challenges. This paper will focuses the technical concepts, need of SBSP, ,the history and developmentsin India and other countries. This paper will conclude its technical and historical overview with a review of possible solutions to the technical and financial challenges of SBSP. Finally, this paper will outline the current regime of international space law explaining how it applies to SBSP, while offering suggestions for how this regime can improve.

I. WHY SBSP

One solar power satellite could provide 1 gigawatt of continuous power, enough to power 500,000 homes, also the equivalent of a large nuclear power plant. Like a nuclear power plant, SBSP would do so without emitting any carbon dioxide into the atmosphere. Unlike a nuclear power plant, SBSP would do so without any radioactive waste by-product or danger of nuclear meltdown. Unlike ground-based solar, without the interference of the earth's atmosphere, a solar power satellite could collect 7-10 times the amount of power. The sun's rays would shine continuously on a solar power satellite, thus this power could be supplied continuously without interruption. Solar power satellites could then transmit that power anywhere in the world. These are 2 properties that set SBSP apart from other renewable energy sources. Ground-based solar power requires a power storage system to supply power when the sun is blocked by bad weather or during the night which adds to its cost and decreases its efficiency. Wind power is often available only from remote or offshore locations. Even countries with minimal energy infrastructure or people located in remote areas could install receivers to get a continuous power supply from SBSP.

II. SBSP IN INDIA

2.1 Energy Concerns in India

Depleting fossil fuel reserves and the tangible impact of climate change have mandated nations to review their energy policies. The Government of India has reviewed energy-mix policies at the highest level. Their target is to achieve a target of 932 GW installed power capacity by 2052, as required for an average 5.5% GDP growth rate in the longer term. To accomplish this, the annually installed power capacity in India has to grow at increasing rates from the current 6 GW/annum to about 20 GW/annum by 2032 and 31 GW/annum by 2052.

The constraints on growth of power capacity (like land availability and its acquisition, water and fuel supply chains (for coal as well as nuclear power) and silting of dams etc, are the major factors that have, so far, limited power capacity growth in India to a maximum of about 6 GW/year. While fossil fuels like oil and natural gas are now depleting, the 21st century is likely to witness global depletion of coal reserves in India as well. There are also limits in India (about 100GW) to available renewable(non-solar) energy sources like wind, biomass, and ocean thermal/wave energy.

2.2 India's National Solar MissionFor Terrestrial Solar Power Stations

Emphasis has now emerged in India on terrestrial solar power that is clean and perennial. 1% of India's land area when efficiently harvested for solar energy could yield a maximum output of about 800 GW of electric power. India's recently announced National Solar Mission targets 20GW terrestrial solar power by 2020, 100GW by 2030, and 200 GW by 2052. Assured budgetary support of the government through a Non-Lapsable Solar Fund sourced from the consolidated fund of India enhanced by tax levies on fossil fuel and fossil fuel generating plants, would provide an immediate start-up fund of $ 1.0 billion (including demonstration plants), $2.5 to3.0 billion by 2017, and $ 13-21 billion over next 30 years.

2.3 Space Based Solar Power Stations

However, the availability of terrestrial solar power is constrained to an average5.6 sun-hours per day in India. As a result, India's National Solar Mission target of200 GW terrestrial solar power by 2052 is actually equivalent to about 36 GW of peak generating capacity, when viewed on a 24x7 basis. Solar energy harvested in space is now recognizable as an option for a 24x7 source of clean, perennial, abundantly available power.

For India to attain at least 90% of the standard of living of one of the developed nations (such as France) a 7% GDP growth rate is essential. Recent studies indicate that as an "insurance policy" to meet potential shortfalls in achieving power capacity growth targets from all terrestrial sources, and for a GDP growth rate of 7%, about544 GW of solar power from space based stations by 2052 would be required. Such an SSP profile could almost double India's GDP per capita, and deliver a net GDP benefit to the nation of over $100 trillion. The net carbon emission avoided by this SSP growth profile could be about 66 million tonnes, thus adding to global climate change mitigation efforts.

III. BASIC CONCEPTS

Space-based solar power (SBSP) is the concept of collecting solar power in space (using an "SPS", that is, a "solar-power satellite" or a "satellite power system") for use on Earth. It has been in research since the early 1970s.

Figure 1 shows Basic elements of space based solar power.

Space-based solar power essentially consists of three elements:

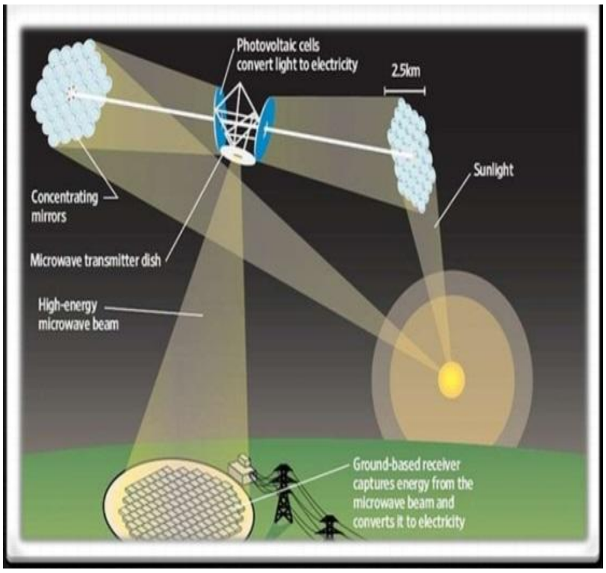
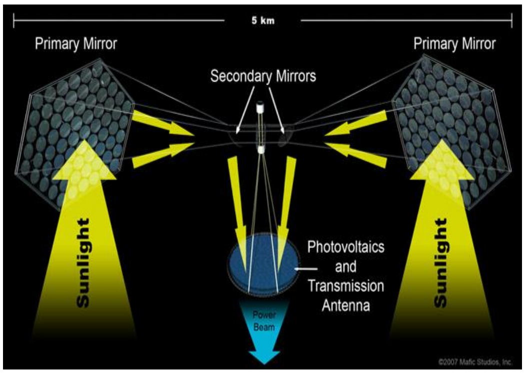


Figure 1. :Basic elements of SBSP

- a means of collecting solar power in space, for example via solar concentrators, solar cells or a heat engine
- a means of transmitting power to earth, for example via microwave or laser
- a means of receiving power on earth, for example via a microwave antenna (rectenna)



Wireless power transmission was proposed early on as a means to transfer energy from collection to the Earth's surface, using either microwave or laser radiation at a variety of frequencies.

3.1 Microwave Transmitting Satellites

Microwave transmitting satellites orbit in geostationary orbit (GEO), about 35,000 km above Earth's surface. Designs for microwave transmitting satellites are massive, with solar reflectors spanning up to 3 km and weighing over 80,000 metric tons. They would be capable of generating multiple gigawatts of power, enough to power a major U.S. city.

The long wavelength of the microwave requires a long antenna, and allows power to be beamed through the Earth's atmosphere, rain or shine, at safe, low intensity levels hardly stronger than the midday sun. Birds and planes wouldn't notice much of anything flying across their paths.

The estimated cost of launching, assembling and operating a microwave-equipped GEO satellite is in the tens of billions of dollars. It would likely require as many as 40 launches for all necessary materials to reach space. On Earth, the rectenna used for collecting the microwave beam would be anywhere between 3 and 10 km in diameter, a huge area of land, and a challenge to purchase and develop.

3.2 Laser Transmitting Satellites

Laser transmitting satellites, orbit in low Earth orbit (LEO) at about 400 km above the Earth's surface. Weighing in at less than 10 metric tons, this satellite is a fraction of the weight of its microwave counterpart. This design is cheaper too; some predict that a laser-equipped SBSP satellite would cost nearly $500 million to launch and operate. It would be possible to launch the entire self-assembling satellite in a single rocket, drastically reducing the cost and time to production. Also, by using a laser transmitter, the beam will only be about 2 meters in diameter, instead of several km, a drastic and important reduction.

To make this possible, the satellite's solar power beaming system employs a diode-pumped alkali laser. First demonstrated at LLNL in 2002 -- and currently still under development there -- this laser would be about the size of a kitchen table, and powerful enough to beam power to Earth at an extremely high efficiency, over 50 percent.

With laser beams, as with microwaves, large reflectors will be used to collect sunlight. But uniquely, the energy of the sunlight itself will be used at the collection point as excitation energy for the laser beams. This would allow us to keep the structure simple, and therefore reduce the size and weight of the orbiting power plant.

While this satellite is far lighter, cheaper and easier to deploy than its microwave counterpart, serious challenges remain. The idea of high-powered lasers in space could draw on fears of the militarization of space. This challenge could be remedied by limiting the direction that which the laser system could transmit its power.

At its smaller size, there is a correspondingly lower capacity of about 1 to 10 megawatts per satellite. Therefore, this satellite would be best as part of a fleet of similar satellites, used together.

3.3 Orbital location

The main advantage of locating a space power station in geostationary orbit is that the antenna geometry stays constant, and so keeping the antennas lined up is simpler. Another advantage is that nearly continuous power transmission is immediately available as soon as the first space power station is placed in orbit; other space-based power stations have much longer start-up times before they are producing nearly continuous power.

A collection of LEO (Low Earth Orbit) space power stations has been proposed as a precursor to GEO (Geostationary Orbit) space-based solar power.

3.4 Earth-based receiver

The Earth-based rectenna would likely consist of many short dipole antennas connected via diodes. Microwave 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 are also considerably greater. Rectennas would likely be several kilometres across.

IV. HISTORY & DEVELOPMENTS

4.1 Origin of Space Solar Power Concept.

The concept of, and early designs for space-based solar power stations emerged from the US in the early-1970s. The pioneer in this area was Dr Peter E Glaser. US government studies in the latter1970s advocated 60 SSP stations for the US each delivering 5 GW of power at the bus bars on ground. This was a significant fraction of US electricity use. Even this tremendous amount of power still represented a small fraction of the enormous annual energy consumption of the US. However, by 1980-1981, the receding oil shock of the 1970's, the lack of demand for alternative energy, and new priorities for US space programs soon ended funded work on space-based solar power in the US.

4.1 Solar Cell Efficiency.

Over the decades, since the 1970's, considerable advances have been made in enhancing solar cell efficiencies and reducing costs. It is expected that by 2020, electricity from advanced solar concepts, such as nanotechnology-based solar cells in commercial production, are likely to be competitive with power generated from fossil fuels. Also, the efficiency of solar energy conversion would be comparable to the efficiency figure of coal energy conversion. However, on the ground, solar arrays operate for no more than 6-8 hours per day, on average; and this necessitates the need to examine SSP systems as a promising alternative to meet the base load power demands.

4.2 Progress in India on SSP.

The need for space based solar power stations was identified in India as early as 1993 (1-5), in anticipation of the emerging global energy crisis of the 21st century. As early as 1987, work was begun in India on advanced space transportation system design concepts for affordable space solar power. The technology for building and orbiting space solar power stations is complex, politically sensitive, technologically and administratively challenging, and may take 10-15 years to be comprehensively demonstrated in space. (Although this may be accomplished in less than 10 years, depending on funding.)

India is among a few space-faring nations of the world who have the capability to effectively participate in global missions for space solar power and related space transportation systems. Dr APJ Abdul Kalam, former President of India, noted that

"…however solar flux on earth is available for just 6-8 hours every day whereas incident radiation on space solar power station would be 24 hrs every day. What better vision can there be for the future of space exploration, than participating in a global mission for perennial supply of renewable energy from space? Space based solar power stations have six to fifteen times greater capital utilization than equivalent sized ground solar stations. Linking Space solar power to reverse osmosis technology for large-scale drinking water supplies could be yet another major contribution of Space…."

At an International Conference on High Speed Air & Space Transportation jointly organized in Hyderabad in June 2007 by the Aeronautical and Astronautical Societies of India, the Conference Panel leaders from India's Defence Research and Development Organization (DRDO) and the Indian Space

Research Organization(ISRO) advocated a global aerospace and energy mission. They placed on record their Recommendation that

"…there is a need to generate a national consensus for the Global Aerospace & Energy Initiative, determine the sources and uses of funding, and evolve a suitable management structure and system to plan and implement the mission…"

NASA Studies on SSP.During the 1990s, new technologies and new concepts led NASA to re-evaluate the space solar power option. During 1995-1997, NASA took a "Fresh Look" at space solar power, in the light of numerous advances made in systems architectures, solar cell mass and efficiency, light weight array structures, robotics, electronics, and materials and concluded that the technological state-of-art was adequate to justify more-aggressive research and development with the goal of demonstrating cost-effective SSP systems.
SSP Studies & Programme in Japan.Throughout the late 1980s, the 1990's,and the early years of the 21st Century, Japan has continued to make quiet, but impressive advances in several of the specific technologies needed for space solar power systems. These have been coupled with various systems studies. It is note worthy that Japan, has the same population density and hence land availability constraints as India. On 28 June 2009, Japan announced a new suite of national space goals, which included space solar power. Nearer term objectives for Japan in SSP include the development of key technologies, a low Earth orbit demonstration, and the conduct of a new round of systems studies. All of the above have the objective of informing a national decision on the development of an operational solar power satellite within the next 5-10 years.
Japan's Aerospace Exploration Agency (JAXA) has committed to developing SBSP and plans to place a 1 gigawatt solar power satellite in geostationary orbit by 2030. JAXA hopes to have a working 1-2 megawatt prototype within 10 years. In JAXA's advanced mission research centre some 180 scientist are already working on the scheme. JAXA is willing to develop the technology on its own but believes the ideal arrangement would be working together with NASA and the European Space Agency.
SBSP development in private companies
Another SBSP company, Solaren, recently signed a power purchase agreement with Pacific Gas & Electric planning to provide them 200 megawatts of electricity over 15 years beginning in 2016. Another company, the Space Island Group, wants to use technology already developed by NASA to build orbiting space stations out of empty fuel tanks discarded by shuttles reaching orbit

V. TECHNICAL AND FINANCIAL CHALLENGE

Cost:
The key barrier to implementation of space-based solar is the literally sky-high cost of launch. Unfortunately, information on the size and configuration of payload space on common rockets is not publicly available, as it is competition-sensitive. However, we can assume that establishing any space-based solar platform would require numerous launches of moderate-sized rockets; these range from approximately \$60 million per launch for a Space X Falcon 9 to \$200 million for a United Launch Alliance Delta IV. Present electricity rates are on the order of \$0.10 per kWh; the provider would have to sell between 0.6-2 gigawatt-hours of energy just to recoup the price of launch. This is prohibitive.
As the private space industry expands costs are expected to fall significantly in the coming decades. High initial launch costs could also be alleviated if they were distributed amongst a larger group of participants joined by their interest in creating SBSP.
Physics:
An estimation of the price of space-based solar energy relies on a better understanding of the physics of light transmission through an atmosphere and the performance of terrestrial solar panels. Typical panels are collecting light about 29% of the time, due to day and night cycles, positioning, and weather. As noted above, a collection satellite in GEO is illuminated 99% of the time; our current factor of improvement is therefore 3.4. Moreover, with no atmosphere to interfere with light transmission from the sun, light intensity in orbit is 144% that available on Earth. Considering both duration and intensity, our total factor of improvement for light received per unit area is 4.92. In other words, five square meters of a terrestrial panel produce the same energy as one in orbit. Given the costs, difficulty, and hazards of placing these panels in space, it is difficult to imagine widespread adoption given that the improvement is a factor of five - even before we consider losses from transmission to ground.
Prohibitive launch costs remain the number one technical and financial barrier to SBSP though it seems over time this problem will diminish. Improving the international legal framework governing space law is of equally important to the realization of SBSP.

VI. INTERNATIONAL SPACE LAW: FRAMEWORK AND CHALLENGES

The idea of SBSP naturally raises serious questions concerning what norms of international law should be applicable to solar power satellites in space. These questions include property rights in space, rights of private parties, liability for damage, and coordination and registration of space objects. The general framework to answer these questions already exists, but further development will be needed. The United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) has led the development of this legal frame work. Presently there are three treaties relating to outer space significant to SBSP.
The first and most significant is the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space (Outer Space Treaty. Second is the Convention on International Liability for Damage Caused by Space Object (Liability Convention). Third is the Convention on Registration of Objects Launched into Outer Space (Registration Convention).

6.1. Outer Space Treaty

The Outer Space Treaty has been accepted and ratified by over 100 countries including all current space faring nations.

The Outer Space Treaty creates the fundamental base of outer space law under the idea that outer space is the common heritage of mankind. Thus, the exploration and use of outer space shall be free for exploration and use by all states. This means outer space, including the moon and other celestial bodies, is not subject to national appropriation by any means. Thus, even for countries that currently lacks the resources to reach outer space, the right of exploration and use remains available to them as they become capable of space exploration.

Though a state cannot claim ownership outer space or any celestial bodies within, a state on whose registry launches an object into outer space retains jurisdiction and control over that object. The ownership of such objects in outer space is also not affected by their presence in outer space or by their return to earth. Thus, countries, or companies that launch satellites on their state's registry retain ownership of that satellite. If no such ownership interest existed there would be no incentive to send a satellite into space that could be appropriated by another country or private party.

The basic premise of the Outer Space Treaty involves actions by states. However, it does contemplate the actions of private companies in two sections. First, parties to the treaty agree to bear international responsibility for national activities in outer space, whether those activities are carried out by governmental agencies or by non-governmental entities. Second, states or their nationals are required to seek international consultation in circumstance that could cause harm to other states. Though space exploration was dominated by states in 1968 the Outer Space Treaty still contemplated private companies joining the states in space travel.

6.2. The Liability Convention

The Liability Convention helped clarify the liability of states and private parties for damage in space. The Liability Convention has been approved and ratified by 91 countries including all current space faring nations.

The Liability convention states that a launching state shall be absolutely liable for damage caused by its space object on the surface of the Earth or to aircraft in flight. However, a state will only be liable for damage caused elsewhere than on the Earth's surface to a space object of another launching state, if the damage is due to its fault, or fault of persons for whom it is responsible. The Liability Convention specifically excludes nationals of a launching state from liability for damage caused. Thus countries have to create their own laws regulating private companies to protect themselves in the case that a company causes damage. If such regulations are not created it could discourage a country from allowing a private company to go to space for fear of international liability. The U.S. and Japan offer two similar but significant solutions to this problem.

The U.S. passed the Commercial Space Launch Act of 2004 (CSLA) granting the Federal Aviation Administration (FAA) the authority to regulate commercial space flights with the interest of promoting private space development while shielding itself from liability. Prior to launching an object into space a private company has to apply for a license from the FAA. The CSLA requires all license applicants to demonstrate financial responsibility, though liability insurance or independent means. The U.S. requires insurance to compensate another party for damages or itself for losses stemming from an activity carried out under the license. A licensee is required to obtain sufficient insurance to cover maximum probable loss estimated by the U.S, but the total amount of insurance will not exceed $500 million. If the damage exceeds $500 million, the U.S. will cover the remainder up to $1.5 billion but only "to the extent provided in an appropriation [bill]." Thus anything over $1.5 billion would need to be covered by the company. If not enough money is allocated in an appropriations bill the company will be liable for all damages. It is important to note the CSLA does not require insurance for loss of the private company's property, only for liability of damage caused to another. However, CSLA helps to protect the U.S. from liability from private accidents, while still giving private companies a potential cushion from liability in the case the damage caused exceeds $500 million. The CSLA helps resolve the potential liability problem caused by the Liability Convention for the U.S. with private companies seeking to launch commercial spacecraft.

The Liability Convention could improve by further clarifying when a party would be liable to another for damages. For example, the Liability Convention fails to define the term "fault" in the context of liability for damage caused in outer space. Because fault is not well defined it is difficult for countries or companies to determine when another party would be at fault for damage to their property in space. A narrow definition of fault could see a country escape liability for damage caused in space, when liability could have been found under a broader definition. This could be especially troubling for a company that invests billions of dollars into SBSP only to have their satellite destroyed by space debris left behind by an old satellite. The U.N. and member states should work to clarify the meaning of "fault" so that countries and companies can more easily predict their potential liability. The international regime should continue to develop a more sophisticated framework for determining liability for damages to protect the property and investments of countries and companies around the world. This could include requiring countries to clean up or retrieve broken or decommissioned satellites or face strict liability for any damage they cause. This could also include improving dispute mechanisms between countries and placing penalties on those refusing to pay proper judgments. Penalties for refusal to pay for damages could help ensure compliance for damage awards, incentivizing countries and companies to promote safe practices, while lowering the risk of catastrophic losses.

6. 3.The Registration Convention

As more satellites enter the Earth's orbit the U.N. and its members recognized the necessity of registering all space objects in one registry to help prevent accidental collisions in space. The Registration Convention has been approved and ratified by 53 countries, including all current space faring nations. The Registration Convention requires all countries to create and maintain a registry of all objects they or their nationals have launched into space. The country then must give this information to the U.N., including the object's orbital parameters. The U.N. takes this information and makes a global registry. Countries can then consult with the registry to ensure future satellites will not interfere with current ones.Private companies seeking to send a satellite have to consult with their country and ensure their satellite enters into their domestic registry and is then submitted to the U.N.

Though the U.N. maintains a general registry of satellites, as more satellites are sent into space a simple registry may not be sufficient in the long term. The international regime will likely need to develop a space traffic control that has the authority and ability to track numerous satellites in orbit, assign orbital slots equitably, and establish transit corridors for new satellites to safely reach orbit. Without such a development space travel could become more dangerous, and an increase of the frequency of collisions could add to the costs or security of SBSP.

VII. CONCLUSION

Space energy is not the only option for solving the world's future energy needs, but it is one of the most promising. The idea of satellites sending clean continuous power from the sun may still sound like science fiction, but many of today's technological marvels in the past likely did as well. The factors outlined above make it clear that space-based solar power is not an immediate solution to our energy challenges. High costs and unproven technology (the microwave transmission system) stand in the way, and the increase in power generation is not nearly enough to justify the effort. However, if these challenges were miraculously overcome, we should consider that it took several Shuttle missions to launch the acre of panels that make up the International Space Station's ~100 kW generation capacity The international legal regime needs to develop further to accommodate SBSP. SBSP will likely also require substantial cooperation between different countries and private companies. All are difficult challenges but will be rewarded with a worthy prize.

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