KALAM-NATIONAL SPACE SOCIETY ENERGY TECHNOLOGY UNIVERSAL INITIATIVE

An International Preliminary Feasibility Study on Space Based Solar Power Stations

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The following paper summarizes the "state of play" for the US and India vis-à-vis space and energy – two critical topics that are typically not linked, but perhaps should be; the paper concludes with a focused proposal for an international, pre-feasibility study of a revolutionary concept for sustainable, carbon-neutral global energy: space-based solar power.

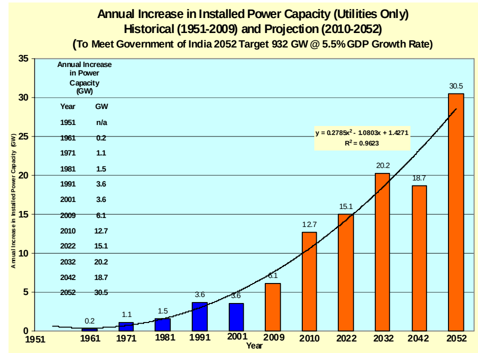
Energy Concerns in the US

Depleting fossil fuel reserves and the tangible impact of climate change have mandated nations to review their energy policies. US experts consider that energy diversification is a national security imperative. According to the Energy Information Administration, the U.S. imports about 60% of its oil, with more than two-thirds of it used for transportation. Oil is essential to the basic functioning of the global economy, from the production of goods in factories overseas and across the country to their delivery to local markets. US experts avow that without oil its military would not be able to defend the country from external threats. In short, the US is now critically dependent on this non-renewable and potentially vulnerable resource. However, those same experts observe that America's long-term security ultimately requires intelligent public policy in support of a vibrant domestic market for renewable energy.

Thus, dependence on foreign sources of energy has made America vulnerable to serious threats to national security. To minimize such vulnerabilities and the moral and security dilemmas they create, US experts now strongly advocate that the US must put an end to the pursuit of fossil fuels across these war-torn and politically volatile parts of the world. *They emphasize that as a matter of civic responsibility and obligation to the men and women who keep the US secure, the American people should press their elected representatives to accelerate the transition to a clean energy economy.*

It is noteworthy that Alexander Hamilton, one of the Founding Fathers and the first Secretary of the Treasury, was a strong advocate for government support of industrialization as a matter of national security. *The case for government support to the renewable energy industry is no less urgent but will require sustained public pressure from across the political spectrum against entrenched private interests conflicting with the national interest.*

Energy Concerns in India



A similar situation exists in India with respect to the depletion of fossil fuel reserves and the impact of climate change. 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.

India's National Solar Mission For 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, 100 GW 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 to 3.0 billion by 2017, and $ 13-21 billion over next 30 years.

India's National Solar Mission envisages aggressive pursuit of R&D through solicited Research in identified thrust areas, including storage systems; industrial research for increasing efficiency and reducing costs; basic research in new materials and concepts; a consortium approach by networking of R&D efforts by different Ministries of Government and international cooperation in research and development

Space Based Solar Power Stations

However, the availability of terrestrial solar power is constrained to an average 5.6 sun-hours per day in India. As a result, India's National Solar Mission target of 200 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%, about 544 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.

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 latter 1970s 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.

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.

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…."

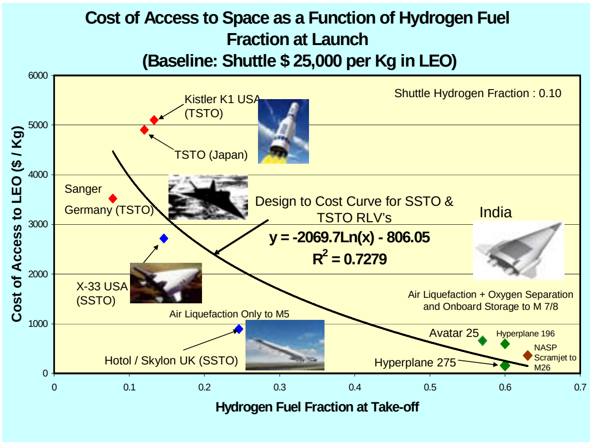
At an International Conference on High Speed Air & Space Transportation jointly organized in Hyderabad in June 2007 by the Aeronautical and Astronautical Societies of India, the Conference Panel leaders from India's Defense Research and Development Organization (DRDO) and the Indian Space Research Organization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

Space Transportation: A Critical Factor in the Cost of Energy from Space



The cost of transportation for a space solar power plant into low earth orbit (LEO), and then subsequently transferring it to its operational orbit accounts for not less than 1/3rd of the initial capital cost for the plant. On 7 September 2000, NASA testified to the US Congress that that recurring launching costs ***in the range of $100-$200 per kilogram*** of payload to low-Earth orbit would be needed if SPS are to be economically viable. More recent estimates have placed the launch cost target in the range of $400-$800 per kilogram. Similar estimates had been made earlier in the UK and India. Clearly, low cost launch is essential to the economic viability of the solar power satellite concept. *Up to this point, no nation has developed and tested space launch vehicles to meet these aggressive cost targets.*

India's interest in SSP originated in 1987, with the conceptual design of a Single Stage to Orbit fully reusable aerospace vehicle called the "Hyperplane". Since the development of the partially-reusable US Space Shuttle in the 1970s, over 22 reusable aerospace launch vehicles have been designed the world over. However, none have been made operational so far. Recently, ISRO has taken up a programme to develop an RLV Technology Demonstrator somewhat on the lines of Japan's "HOPE" concept.

The ***cost of access to space*** depends on a host of factors, principally, the reusability of the vehicle and its hydrogen fuel fraction. Above all, if significant total R&D investment is to be amortized in commercial service, the cost of access to space depends on the size of the market for space applications, as measured in tonnes of mass flow every year into space. Currently the cost of access to space is $25,000 per kilogram for the Space Shuttle, which has a hydrogen fraction of 10%, a payload fraction of 1.5% and is reusable about 10-100 times per airframe, with major refurbishment following each flight. To achieve a cost of no more than a few 100s of dollars per kg in LEO, an SSP transportation system has to be reusable at least 100-1,000 times (with significant refurbishment between flights), and to have a payload fraction at least 5-10 times that of the Space Shuttle; namely, 7%-15%.

Studies in India and by others in the international aerospace community have indicated that such high payload fractions are attainable *only when the vehicle carries no liquid oxygen on board at take-off, but collects and liquefies oxygen while climbing to orbit in hypersonic flight regime.* (6 - 17) For example, a study by scientists at the Applied Physics Laboratory (APL) of John Hopkins University (JHU) in 1964 reported payload fractions as high as 30% when air is collected, and liquefied oxygen separated and stored as the hypersonic vehicle accelerates from Mach 5 to Mach 7 in atmospheric flight. India's reusable launch vehicle design studies in 1987-

1996 independently reported 4-12% payload fractions, depending on the take-off weight of the vehicle.

Proposal for a Joint Universal Energy Technology Initiative

In view of these late 20th and early 21st century developments in the energy and aerospace sectors of several national economies, it is proposed that India, the US and other nations work together to establish an enduring, firmly integrated consortium of stakeholders from economically strong and weaker nations, in order to further the development of international space-based solar power stations and various required enabling technologies such as safe, affordable and reliable access to space, wireless power transmission, advanced in space operations, and others.

However, space science, technology and applications cover a very vast area of systems and missions; including, space exploration, Earth observations, space industrialization and space security. Just as a given lake can contain only a definite amount of water out of the almost infinite quantity of water in the universe, even so, in order to make a significant entry into large scale revenue-earning space applications that have universal applications, progress can be made more effectively if the interested countries proceed with an appropriate recognition of the obstacles that have in the past impeded rapid technology advancement in these areas. The revolutionary idea of space solar power must be approached systematically and cautiously; with a proper regard for establishing feasibility and economics at each stage.

The steps forward proposed here are to be taken up in a self-renewing manner in several phases:

1. **Phase 1:** An International Preliminary Pre-Feasibility Study (1-year)
2. **Phase 2:** A Detailed International Feasibility Study, coupled with a range of targeted Engineering Demonstrations on Ground and Technology Experiments in Space (5-7 years).
3. **Phase 3:** Development and Deployment of one or more initial Space Solar Power Pilot Plants, capable of delivering meaningful power to terrestrial markets.
4. **Phase 4:** Space Solar Power (and supporting infrastructure) Industrialization (self-sustaining & self-renewing far into the future)

Core Competencies & Competitive Advantages of India & US in New Energy Technology & Applications

The proposed International Preliminary Pre-Feasibility Study of SSP and key supporting infrastructure, particular the RLV, would initially draw on economic factors, conditions and technological strengths in India, the US and other participating countries to contribute to global developments in solar power from space. These are:

(a) Large unfulfilled demand for power, heating/cooling, and transportation fuels in India. the US, and indeed in all nations.

(b) Serious fresh water shortages in coastal cities of India, and elsewhere in the world - a most compelling and currently critical necessity for alternate sources for pure drinking water for large populations.

(c) Demonstrated capabilities and capacities in both countries for design and manufacture of large electric power systems, capabilities to design and manufacture solar photovoltaic technologies and systems, microwave technology for power transmission, off-shore engineering, sea water reverse osmosis technology, software design development and applications.

(d) Tremendous relevant research and development capabilities in various interested countries, including substantially low cost research and development base in India in advanced technologies related to new energy and enabling technologies.

(e) Innovative and novel design concepts from India and other countries for small, fully reusable aerobic spaceplanes as potential pathfinders for low cost access to space.

(f) Demonstrated low cost, reliable space technology and spacecraft engineering and technology capabilities in both countries now being extensively used for sustainable economic development, including geo-stationary satellite launch capabilities.

(g) Established capabilities and experience in both countries in ground segment technologies and systems, such as space vehicle launch stations (spaceports), spacecraft control facilities, portable terminals for real-time applications etc.

(h) Demonstrated research, design, development and manufacturing strengths in aeronautical and aerospace engineering in both countries, with a preponderance of capacities in the US

(i) Established financial and managerial capabilities for taking up large International programs in the US and emerging program management capabilities of a similar nature in India.

Phase 1: Scope of Work of a Preliminary Pre-Feasibility Study on Space Solar Power and Low Cost Space Transportation

The scope of work of a detailed Systems Engineering and Techno-Economic Pre-Feasibility Study on Space Solar Power and Low Cost Space Transportation for India may be as follows:

1. **Energy Economics In India, China, US and Japan as Related To SSP.** This part of the effort would comprise activities such as a general study on the energy situation in India in the context of need for SSP, the economic impact of SSP on India and other nations in the context of the country's demand and supply situation for energy up to 2050, India's plans for renewable energy systems, and the integration of space and ground based solar energy systems for India. For example, the study should establish the short term and long term goals for SSP energy requirements in India and the nation's capacity to pay for the technology and energy.

2. **Market In India, the US and other Nations For Energy From Space.** This work package would include detailed study of the market size and characteristics in India, the USA and other nations for Energy from Space, and its niche applications, for example, like a Drinking Water Mission for coastal cities in India and a mission to alleviate shortages of both drinking water and agriculture irrigation water on America's increasingly parched and heavily agricultural West Coast.

3. **SSP System & Technology.** This work package would include study of the design and technology of the SSP (including power beaming) – the Systems Architecture best suited for this world's first SSP mission, the technologies required, their sources, cost, time for development of a Technology Demonstrator (on ground and in space); potential environmentalist resistance, strategy to meet this; approvals needed from International bodies and the means to get them. Requirements and projects for Proof-of- Concept demonstration of critical technologies for SSP systems & technologies

4. **Space Infrastructure, Transportation System and Technology.** This part of the study would focus on space transportation and space construction requirements. How existing expendable launchers available in India, France, the USA, and Russia may be used for the early SSP space system demonstrator (with a cost subsidy). How India's aerobic RLV concept, or that of any other country, may be considered as potential solutions to the problem of low cost commercial space transportation. The Systems Design best suited for this world's first SPS-mission specific commercial space transportation system, the technologies required, their sources, cost, time for development of a Technology Demonstrator (on ground and in space). Requirements and projects for Proof-of- Concept demonstration of critical technologies for key infrastructure, such as RLV systems & technologies.

5. Approvals needed from world governments and international bodies and the means to get them. This aspect of the study would address how precisely such work can be carried out as an open, unclassified international project with whatever safeguards are needed from the point of view of proliferation concerns, the US International Trade in Armaments Regulations (ITAR) and other restrictions. It would address options available for space construction for the SPS techno-commercial demonstrator. The effort would focus particular attention on the need to secure spectrum to allow R&D related to wireless power transmission to proceed as soon as possible.

5. **Preliminary Feasibility Report.** The study would result in a Preliminary Pre-Feasibility Report, addressing the techno-economic feasibility of space solar power and low cost space transportation technical feasibility & commercial viability report: a preliminary pre-feasibility report integrating the above studies.

Institutional Contributions

Institutional contributions in the areas of space based solar power, space infrastructures, and low cost space access are proposed as suggested in Table 2; presented below are the prospective areas for the US and India only. Contributors from Japan, Europe, Canada, and other space-faring nations, such as Russia, Australia, the United Kingdom, and China' and, various emerging energy market countries in North Africa, South Africa South America (e.g., Brazil), and the South Pacific would emerge progressively.

Table 1: Potential International Contributions

System of Systems	India	US
Space Based Solar Power Stations	(a) Indian Space Research Organization-Indian Satellite Applications Centre (ISRO - ISAC), Bangalore (b) National Solar Mission Authority (MNRE), New Delhi (c) Indian Institute of Technology (Madras) and its Technology Park (d) Indian Institute of Technology (Mumbai) (e) Petroleum University, Centre for Energy & Aviation Studies, Dehra Dun (f) Bharat Electronics Ltd, (BEL) Bangalore (g) Electronics Corporation of India Ltd (ECIL), Hyderabad (h) Electronics &Radar Development Establishment (LRDE), Bangalore (i) Non-profit organizations like the Aeronautical and Astronautical Societies of India (j) Universities	(a) National Aeronautics and Space Administration (Various Field Centers) (b) US Department of Energy, including ARPA (E) (c) Aerospace Industry (e.g., Boeing, Lockheed, etc.) (d) The US Energy Industry (e) Universities (f) Small Companies (g) US non-profit organizations, such as the National Space Society
Low Cost Space Transportation	(a) Indian Space Research Organization-Vikram Sarabhai Space Centre (Thiruvanathapuram) (b) Aeronautical Development Agency (ADA) Bangalore (networked to related the chain of National Laboratories in India including National Aerospace Laboratory, Bangalore and Defence Laboratories) (c) Hindustan Aeronautics Ltd , Bangalore (networked to related aerospace and engineering industries in India) (d) Indian Institute of Technology (Mumbai) (e) Indian Institute of Technology (Kharagpur) (f) Indian Institute of Technology (Madras) (g) Indian Institute of Science, Bangalore (h) Other Universities	a. National Aeronautics and Space Administration (Various Centers, including NASA MSFC, JSC, KS, etc.) b. US Department of Defense, including DARPA c. Aerospace Industry (e.g., Boeing, Lockheed, etc.) d. Universities

Cost of the Preliminary Pre-Feasibility Study. As far as possible, the stakeholders in this Study would be called upon to carry out the study within their own technical and financial resources (i.e. there need be no money transfers across nations, although there may be joint activities among participating countries).

Action Plan

In order to move forward, a definite Action Plan is essential; the final details of which must be resolved through future country-to-country discussions. The approach suggested here is as follows:

1. The US, India and any other immediately interested countries should finalize this Framework for carrying out Preliminary Pre-Feasibility Studies by exchange of e-mails and/or teleconferences.
2. Each side should identify experts in the various fields of expertise required, and should make internal arrangements to empower them (administratively and financially) to work for this International Study. Lists should be exchanged and specialist task teams should be set up for various aspects of the Study
3. A formal Study Task Team Network should be set up, a Virtual Network that is formally recognized and authorized by their institutions and functions without encroaching on the institutional system of management
4. Creative discussions between the Task Teams should be organized by teleconference; notes and papers should be exchanged (each time with a copy to a central convener/coordinator on each side). Visits if any to other countries should also self-funded.
5. An Editorial Team should be set up by each side; working closely with each other, collate reports prepared by the Task Teams and Draft the Final Report for approval by Dr Kalam and the National Space Society.

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