Issues in Development of Space-Based Solar Power

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Abstract—Space-Based Solar Power—SBSP) is a concept that has considerable potential to provide clean renewable energy. Increased population coupled with reduced natural resources represent a challenge to national and world security. The SBSP concept is to collect energy from the Sun in Earth orbit. The electrical energy is converted to microwave frequency for transmission to the surface of the Earth. There it is converted back in to electricity for use. Possible usages are base-load power, fuel conversion or direct delivery to consumers in isolated locations. The available potential of solar energy is greater than energy in petroleum reserves. The primary issue is defining the path to development of SBSP capability.

A critical parameter is the cost of delivery of components to orbit. There are a variety of concepts with the potential to reduce cost of payload in orbit. It is important to make a commitment to the development of a capability with cost efficiency as the prime objective.

Current technology supports viability of the SBSP. A government-supported proof of concept demonstration would focus initial efforts. There are a number of ideas to be described that fit the demonstration objectives.

Analysis of SBSP has defined certain key questions. Can the SBSP system be designed to be environmentally safe? Can clear targets for economic viability in markets of interest be identified? Are there technical development goals and a roadmap for reducing risk? Selection of design trades could enable the best options.

The government is expected to take the lead in initial action. The transition to commercial application requires a defined vision. This goal needs to be funded with a focus on development of this solution to energy security. [1] [2]

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1. INTRODUCTION

The potential of space-based solar power(SBSP) as a resource to alleviate world energy needs has not been effective in obtaining the political support for a comprehensive program of evaluation and demonstration. An alternative approach is to emphasize the environmental benefits. Not fully understanding the stability of the Earth System and the specific feedback mechanisms controlling our climate, scientists are unable to effectively predict the course of change to the global environment[1]. Geologic records indicate a potential rate of change that leaves civilization vulnerable to severe economic effects in a period of significant population growth.

Solar energy as an alternative to fossil fuel reduces stress on the Earth's environmental system. Cost of solar power, particularly from space, is not competitive with current prices of fossil fuels. Collecting the energy in space provides significant advantages in continuity of supply over terrestrial solar, but there is large initial cost prior to getting a return on the investment. The "Fresh Look at Space Solar Power" study shows that concepts needing less investment in an operational system may be feasible[2]. Resources are needed to develop technology and to demonstrate practicality,

2. POLITICAL ISSUES

Space solar power has been advocated on the basis of its value as a solution to the World's energy problems. This approach does not appear to be effective. Fossil fuels are sufficient to meet most of the needs in the immediate future, hence the lack of support from policy makers for an expensive and complex program. SBSP development as a sustainable energy source with benefit to the environment provides a basis for the initial investment and a transition to a profit making commercial enterprise. The potential for clean renewable energy may induce the policy makers to

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assign resources to the technology development and demonstration. Then, when investment risk is reduced, the burden of funding by the government may be replaced by private sources. The definition of space solar power concepts that can be implemented with less initial investment also aids in the transition from government to private industry funding[2].

Through an emphasis on potential environmental change impacts, political commitment to SBSP support will be put into a context that most stakeholders, the general public, can understand and embrace[3].

Supporters of space-based solar power have been presenting the concepts as a means to help meet world energy needs. This argument has not been effective in garnering support for basic research and technology development. Fossil fuel alternatives have been too cheap and near term effect on the "economy" inhibits action by policy makers. Concern for the environment is greater than the policy makers realize.

Defining a new goal for the space program is a complex process. Of the potential options, the greatest direct benefits may be in dealing with global environmental change. An uncontrolled experiment on Earth system processes is occurring from anthropogenic inputs to the atmosphere[4]. Mankind's activities are inducing modifications to the conditions that have evolved to support current planetary life systems. Incontrovertible evidence of the effects of change may not be established until those changes are far advanced. If global environmental changes are severe in rate and magnitude, the international community will need all of the tools that can be mustered to alleviate the effects on society. SBSP provides an organizational structure for the space program activities to help deal with global environmental change. To reduce the risk in policy implementation, geoengineering strategies need to be fortified by technology development and demonstrations to define the potential benefits and to assess the risks of implementation[6][5].

There is growing awareness of the threat of rapid global environmental change. Scientists are extending their traditional role of theory and observation to emphasize the risks of global change. The risks provide the context for action by policy makers to move toward sustainable systems. The transition to power from space is responsive to the environmental concerns. There is a need to stabilize the Global environment and, consequently, the Earth's economic and social stability.

The "overview effect" from space has played a major role in developing a public sense of the fragile nature of the global environment. Stress on the Earth's environmental system is increasing due to the buildup of carbon dioxide and other greenhouse gases. Models predicting the response to this buildup have not performed well in projecting the effect on the Earth's climate because of the complexity of the system and the feedbacks within the system. Even the direction of climate change has not been predictable because of solar output and volcanic activity. There may be other interactions that are not well defined by the computer models, but that are reducing the stability of the Earth system. Because of the potential influence on the stability of the ocean currents that transport heat from the tropics to the higher latitudes, there is even a risk of returning the Earth to a glacial period rather than the global warming that is the present paradigm. Analysis of glacial ice cores indicates that such a shift can take place in less than a few decades.

The likely effects of rapid climate change are increases in storm intensities, flooding, droughts, regional cropping shifts and sea level rise. These effects will have severe social and economic consequences.

The rate of change and its direction leave civilization vulnerable to severe economic change in a period of significant population growth. Sustainable development has become the mantra for dealing with the potential global crises that are facing civilization. Clean, renewable energy is a resource that meets the criteria of sustainability. Collecting solar energy is a prime candidate. Collecting the energy in space provides significant advantages in continuity of supply, although it's development represents many challenges. A primary challenge is the issue of large initial cost prior to generating a return on that investment. The NASA Fresh Look at Space Solar Power study shows that concepts needing less initial investment are feasible. Even so, early SSP systems are not likely to be price competitive unless fossil fuel pricing incorporates the long-range economic impact.

The risks identified through the rigor of the U. S. Global Change Research Program(USGCRP) must provide the motivation for action toward sustainable systems.[1] The USGCRP is an integrated program documenting the Earth system, understanding Earth system processes and developing computer models to predict the course of changes induced by humans or as the result of natural variations. The program is beginning to analyze the environmental, socioeconomic and health consequences of global change. The obvious next step is to assess means for mitigation of the effects of global change[6]. Schemes to accomplish this mitigation have been termed "geoengineering". They may include steering hurricanes, adding sulfur to jet fuel, preventing tornadoes, but SBSP has a lead role in reducing carbon dioxide input to the atmosphere.

The prosperity of future generations is dependent on a stable global environment. To ensure environmental stability, a continued effort to understand the effect of human activities must be a priority. The complex relationships of greenhouse gases, wind circulation, ocean currents and atmospheric water vapor make the analysis extremely challenging. It is undisputed that carbon dioxide in the atmosphere has increased by over thirty percent since the beginning of the industrial age. Fossil fuels are certainly a major contributor to that increase. By replacing fossil fuel use, SBSP could reduce the buildup of CO_2 in the atmosphere and the consequent climate changes from an enhanced greenhouse effect. There are economic returns from a space-based power source that will lead to commercial management and operation of the system.

There will continue to be an element of the political community that is committed to the short-term view because of the immediate economic impact. This reality is a factor that will have to be dealt with through facts and risk assessment for the long-term view. The anticipated benefit to the Earth's environment is the overarching objective that may provide support for technology development and demonstration toward space-based solar power for use on Earth.

3. TECHNICAL ISSUES

No scientific or technological breakthroughs are needed to develop SBSP. Certain technology may require demonstration such as microwave power transmission through the atmosphere. The primary questions relate to beam focus and efficiency. The challenge will to limit the cost of the required hardware. One of the requirements will be a minimum weight for the particular subsystems that make up the orbital system. This is directly related to the cost of launching the total mass into orbit.

Cheap, reliable access to space is a key issue in making SBSP economically viable. The mass to be deployed will mandate a reusable launch system. Trades of the number of stages will be needed to optimize the efficiency. One evaluation may be the air launch concept being developed by Burt Rutan. It enables the launch of the upper stages above much of the sensible atmosphere. This reduces aerodynamic loads, but may be limited by a reasonable takeoff weight.

Current assembly concepts have assumed construction in low earth orbit. After completion, the solar power satellite would be transferred to a higher orbit. Propulsion to accomplish this is a critical issue. One concept that has the specific impulse to make transfer practical is Variable Specific Impulse Magnetoplasma Rocket(VASIMR).[7] NASA spinoff firm, the Ad Astra Rocket Company, has announced a key milestone in ground testing of its prototype plasma drive technology,

The VASIMR "helicon first stage" - which generates the plasma for acceleration by the rest of the drive , has achieved its full rated power of 30 kilowatts using Argon propellant, according to the company. This paves the way for further trials in which the ion-cyclotron second stage will get to boost the helicon plasma stream to the target power of 200 kW.

The idea of the plasma drives is to use electric power to blast reaction mass (in this case Argon) from its rocket nozzles at a much higher speed than regular chemical rockets can achieve. This means that the carrying spacecraft gets a lot more acceleration from a given amount of fuel. A potential demonstration for VASIMR is maintaining the orbit of the international space station (ISS) without the need to burn large amounts of chemical rocket fuel. This serves as a demonstration of the transfer large structures between orbits.

Since the solar power satellite was studied in the late 1970's there have been many advancements in subsystem technology.[8] These advances have included (a) improvements in PV efficiency from about 10% (1970s) to more than 40% (2007); (b) increases in robotics capabilities from simple teleoperated manipulators in a few degrees of freedom (1970s) to fully autonomous robotics with insect•class intelligence and 30•100 degrees of freedom (2007); (c) increases in the efficiency of solid-state devices from around 20% (1970s) to as much as 70%•90% (2007); (d) improvements in materials for structures from simple aluminum (1970s) to advanced composites including nanotechnology composites (2007); (e) the application to large space structures; (f) high temperature super-conductors and many other technologies may be integrated into the design.

Microwave beams are constant and conversion efficiencies high. They can be beamed at densities substantially lower than that of sunlight. This delivers more energy per area than terrestrial solar energy. The peak density of the beam can be significantly less than noon sunlight, and at the edge of the rectenna equivalent to the leakage of a microwave oven. This low energy density and choice of wavelength also means that biological effects are likely to be low. The safety of wild life wandering into the beam is not expected to be an issue.[15]

The physics of electromagnetic energy beaming is uncompromising. The size of the antenna makes microwave beaming unsuitable as a "secret" weapon. The distance from the geostationary belt is so great that beams diverge beyond the coherence and power concentration needed for a weapon. The beam is likely to be designed to require a pilot beam transmitted from the rectenna site. Absent the pilot signal, the system can be programmed to go into an incoherent mode. Concerns may also be addressed through an inspection regime. The likelihood of the beam wandering over a city is extremely low. Even if it occurred, it would not be a hazard.

Wireless energy transfer by laser beam represents a different set of requirements. To achieve comparable efficiency, the beam must be more intense. The clouds in the atmosphere will reduce the transfer. The intense beam may produce a hazardous level to be avoided by aircraft and satellites. Still for the application to military power supply, it may be a manageable method.

At present, the United States has very limited capabilities to build large structures, very large aperture antennas or very high power systems in orbit. The capability to control and maneuver these systems in space must be developed and demonstrated. Presently, the ability to translate large mass between Earth orbits will be required for deployment SBSP. Eventually, the capability for in•space manufacturing and construction or in•situ space resource utilization may be developed, but at this point it is a challenge that should not be incorporated into the program. One critical item to be demonstrated is capability for beamed power and application to propulsion of large space systems.

4. DEMONSTRATION

The ultimate goal is to enable development of Space-Based Solar Power. A key element in the concept is wireless power transmission [9]. The International Space Station(ISS) is a potential platform for demonstrating power beaming. An initial test could be a transmitting antenna on the Earth's surface with the receiving rectenna on the ISS. A large phased array about 2280 meters in diameter could transmit 10kw of radiated power at 35 Ghz. The flat rectenna on ISS could be 4m in diameter and expected to collect 5kw power. The microwave frequency was selected to take advantage of a dip in the atmospheric absorption and to minimize the flight hardware.

The next level of demonstration of wireless power transfer is to transmit from ISS to the Earth's surface. The ISS installation would include an energy storage module weighing 10,000 Kg. It could be powered from outlets built into the space station for experimentation. The antenna is a 40x60m crossed beam. The system is transmitting up to 100Kw in one minute bursts. The 152 m rectenna can receive the bursts converting about 50Kw. This is intensity within the 5mw/cm^2 safety standard. The 35 Ghz planned for this demonstration is higher frequency than the communications and control bands on the ISS This corresponds to a reduction zone in atmospheric absorptions.

The wireless power transmission demonstration is one of the initial elements of an evolutionary development of SBSP. Advancing and maturing the key technologies and systems concepts for SBSP, a "pilot plant" is a critical step. Some of the central features of an affordable and useful initial SBSP pilot plant in GEO include the following:

• Involve the systems designs expected in the full•scale system.
• Incorporate component and technology solutions that can be proven in preparation for decisions on full•scale system designs;
• Be scalable in some clear and credible way to the full•scale system.
• Involve supporting infrastructures and concepts of operations that lead directly to decisions for future operational systems;
• Be staged in the actual environmental setting expected for the ultimate full•scale systems.

As noted, demonstrating an SBSP pilot plant of this scale in GEO will involve a substantial investment. The cost for this demonstrator would be approximately $8B•$9B, including the goal of using a large•lot purchase of expendable vehicles to launch the pieces of the SBSP demonstrator into space.. Over the three stages, this results in a total cost for this "Pathway to SBSP" of about $10B over 10 years. As a result, it is critical that the SBSP system in GEO should also provide some useful "leave behind" capability that has inherent value.

The SBSP demonstrator envisioned would provide a platform to provide up to 10 MW on demand to locations worldwide. The demonstrator program should also retire the key risks on the path to a full•scale system:

(1) Long distance, high power Wireless Power Transmission (WPT)
(2) Platform Assembly and Servicing
(3) Platform Integration and Thermal Management
(4) In•Space Transportation
(5) Manufacturing Costs for all major Architecture elements

Even though it represents a different set of challenges, laser power transmission is an option that requires definition. A concept to evaluate laser transmission from orbit has been proposed.[8] The project involves the building of two satellite systems concurrently, one "heavy" and one "light." This dual approach using radically different methods assures that technical, legal, financial, or other challenges will not prevent demonstrating wireless power transfer. Both satellite missions plan launch in 2010.

Each satellite is limited to 400 pounds for launch to orbit on Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter(ESPA). To keep the weight of the satellite down, lasers are proposed for power beaming. Microwave systems are deemed too large to achieve the weight limit. Neither the Federal

Communications Commission nor the International Telegraphic Union needs to be consulted for laser energy beaming. Such consultation would be required for microwave frequencies.

The "heavy" satellite mission will place on orbit a satellite that will collect power and transmit to Earth via laser (1.0 or 0.86 microns). In order to keep the size of the solar array light and manageable, several orbits are needed to allow the satellite to store energy and build up a sufficient charge for transmission to the ground receiving station. A bulb will be lighted with energy received from space. The ground receiving station will use of a positive control laser. It allows the satellite to aim its laser precisely at the receiver and to authorize its discharge.

The "light" satellite mission reverses the direction of transmission. The orbiting satellite contains a receiver and a light bulb. It will be powered by a ground-based laser (1.0 or 0.86 microns). Visual observation of the light on the satellite being illuminated during the laser broadcast will indicate success.

A recent ground test was conducted in Hawaii to evaluate the potential of wireless power transmission. It was analogous to the test using the Goldstone antenna. The Goldstone test pointed the microwave beam across a canyon and lighted some football field lights. The efficiency was reported at about 83%. Results of the recent test have not been revealed.

The potential of high temperature super-conductors has demonstration requirements. The idea behind the project is to build a system that reduces outages and disruptions by tapping the current-carrying capacity of high-temperature superconducting (HTS) cables and using systems to automatically adjust to power shifts. Specifically, the long-term objective is to make power grids more resilient by automatically shifting loads and protecting against surges to minimize the occurrence of major outages. The challenge of an orbital demonstration is to show that temperatures are within the superconductivity range. No specific hardware combinations have been identified.

The Thunderstorm Solar Power Satellite (TSPS) is a concept for interacting with thunderstorms to prevent formation of tornadoes[10][4][5]. TSPS benefits are saving lives and reducing property. These benefits are not as sensitive to the system economics as the commercial solar power satellite and justify government investment in space solar power. The TSPS can develop and demonstrate the technology and operations critical to understanding the cost of space solar power. Consequently, there is no direct competition with fossil fuel based power supplies until SSP technology and operations have been demonstrated. Before weather modification can be safely attempted, the fine structure of thunderstorms must be simulated and related to tornadogenesis[11][12][13][14].

5. Environmental Issues

The potential environmental impacts of the various approaches must be studied early enough to help make effective choices between the various technical alternatives. These studies should be led by agencies with the required scientific expertise, credibility, and independence[7]. They should include input from all relevant stakeholders. Environmental studies should be integrated into demonstrations of the technologies and operations. It will provide a basis to minimize the environmental impact in the large•scale SBSP.

The potential electromagnetic levels must be defined and related to a review of all electromagnetic energy exposure effects. Studies should identify and engage with US Government agencies and other academic institutions capable of conducting additional research to address public concern. All environmental stakeholders must be included with input into research objectives. A policy to be open and transparent about the potential environmental impacts of SBSP must be established.

If solar is considered "green" energy, then SBSP may be considered the ultimate green energy. SBSP, if manufactured on Earth (and not in•space using lunar or asteroidal material), will of course have very similar manufacturing/pollution impacts as ground solar. Except much less residual pollution is produced because of reduced solar collection area required by SBSP.

While the advantages of a distributed grid of ground solar are clear, especially for peak power during the middle of the day, space solar has several distinct advantages over ground solar. Space power provides base•load power (the minimum power required by the grid at all times).

Consideration of the benefits to a stable global environment will be a factor in evaluating other impacts. Just as the effect of wind farms on local weather is studied, the effect of the microwave beam may produce variations in the weather. The transit of the beam through the stratosphere must be evaluated. Provisions to make these trades must be included in the program plan.

6. Economic Issues

The economic viability of SBSP is uncertain based on current or projected capabilities. Any future agenda to further develop this concept must factor in a projection of these capabilities. Past investigations of the SBSP concept have indicated that the costs are dominated by placing the facility in orbit[15]. Launch cost in dollars per kilogram must be reduced, primarily by developing a totally reusable system. The component weight in kilograms per kilowatt is directly related, therefore, technology development projections are a factor in cost estimates.

Existing launch infrastructure cannot define the business case, and any assessment made based upon new launch vehicles and formats are speculative. Greater clarity and resolution is required to set proper targets for technology development and private capital engagement. Ideally SBSP can be cost•competitive with other base-load suppliers in developing markets.

The Department of Defense(DOD) appears to be spending more than $1/kWh in forward deployed locations. As an initial customer, DOD can be leveraged to demonstrate technology and operations of SBSP. With this demonstration as a base, commercial investment can be expected to follow.

There are economic returns from a space-based power source that will lead to commercial management and operation of the system[16]. There are options in the definition of a coherent development program. Initial use of SBSP as a source of power for in-space applications is one. Overlapping SBSP with in-space power requirements contribute to setting priorities for engineering research.

7. Summary

Space•Based Solar Power is a huge project. It might be considered comparable in scale to the national railroads, highway system, or electrification project rather than the Manhattan or Apollo endeavors. However, unlike such purely national projects, this project also has components that are analogous to the development of the high•volume international civil aviation system. Such a large endeavor includes significant international and environmental implications. As such it would require a corresponding amount of political will to realize its benefits.

Most of America's spending in space does not provide any direct monetary revenue. SBSP will create new markets and produce new products. Great powers have historically succeeded by finding or inventing products and services not just to sell to themselves, but to sell to others. Today, investments in space are measured in billions of dollars. The energy market is trillions of dollars and will generate substantial new wealth for our nation and our world. Investments to develop SBSP have significant economic spin•offs. They open up or enable other new industries such as space industrial processes, space tourism, enhanced telecommunications, and use of off•world resources.

After the fundamental technological risks have been defined, shifting SBSP from a research and development project to a financing and production program is needed. Several major challenges will need to be overcome to make SBSP a reality, including the creation of low• cost space access and a supporting infrastructure system on Earth and in space. The opportunity to export energy as the first marketable commodity from space will motivate commercial sector solutions to these challenges. The delivered commodity can be used for base•load terrestrial electrical power, wide•area broadcast power, carbon•neutral synthetic fuels production, or as an in•space satellite energy utility.

Solving these space access and operations challenges for SBSP will in turn also open space for space tourism, manufacturing, lunar or asteroid resource utilization, and eventually expansion of human presence and permanent settlement within our solar system.

Space-based geoengineering concepts for environmental countermeasures are a potential supplement to earth-based actions. By defining options and benefits, SBSP may alert decision-makers to the potential of space operations as more than a tool to monitor the course of global change. Within the envelope of environmental protection is the preventing tornadoes concept. It promises early benefits by saving lives and reducing property damage. The principal payoff is projected to be the demonstration of space solar power technology and operations. This can lead to investment by the commercial energy organizations when their technical and operational risk is reduced. Once the potential for clean renewable energy from space is demonstrated, the way will be opened for further exploration and development of space.

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BIOGRAPHY

Lyle Jenkins *is currently a consultant on development of the tornado-taming project. He retired from NASA after 38 years of systems engineering activity. Major projects included Apollo and Space Shuttle. Space construction studies on the Solar Power Satellite concept led to concentration on space telerobotics technology. A vision of the potential for space systems to interact with the global environment motivated an interest in geoengineering. The primary tool for this interaction is Space-Based Solar Power. This led to a concept for preventing tornadoes. Prior to NASA, he was a design engineer on the Atlas ICBM and the Centaur, first liquid hydrogen upper stage. He served as gunnery officer on a destroyer. Education was at University of Kansas and University of California, Berkeley, with a BS and MS in Civil Engineering. . He has published 32 papers and has 1 patent. Recreational activities include tennis, fishing and skiing.*

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