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POSITIONING SPACE SOLAR POWER (SSP) AS THE NEXT LOGICAL STEP AFTER THE INTERNATIONAL SPACE STATION (ISS)

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ABSTRACT
At the end of the first decade of the 21st century, the International Space Station (ISS) will stand as a testament of the engineering capabilities of the international community. The choices for the next logical step for this community remain vast and conflicting: a Mars mission, moon colonization, Space Solar Power (SSP), etc. This examination focuses on positioning SSP as one such candidate for consideration. A marketing roadmap is presented that reveals the potential benefits of SSP to both the space community and the global populace at large. SSP can be seen as both space exploration related and a resource project for undeveloped nations. Coupling these two non-traditional areas yields a broader constituency for the project that each one alone could generate. Just as the ISS may never live up to the claims of its advocates in terms of space research, any SSP program must not promise utopian global solutions to any future energy starved world. Technically, SSP is a difficult problem, even harder than creating the ISS, yet the promise it can hold for both space exploration and Earth development can lead to a renaissance of the relevance of space to the lives of the citizens of the world.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEDS</td>
<td>Human Exploration and Development of Space</td>
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<td>GEO</td>
<td>Geostationary Orbit</td>
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<td>IOC</td>
<td>Initial Operating Capability</td>
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<td>ISS</td>
<td>International Space Station</td>
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<tr>
<td>LEO</td>
<td>Low Earth Orbit</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<tr>
<td>OTV</td>
<td>Orbital Transfer Vehicle</td>
</tr>
<tr>
<td>RLV</td>
<td>Reusable Launch Vehicle</td>
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<tr>
<td>SSP</td>
<td>Space Solar Power</td>
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</table>

INTRODUCTION
Different motivations and constituencies have driven the sundry missions conducted over the more than fifty years of outer space exploration. Within this history there have been cycles where the public popularity of such exploration has exploded and receded. Specifically, over the last few decades outer space has gained an amplified importance to the normal functioning of societies given the increased interconnectivity enabled by telecommunications. The ever increasing ratio of commercial space launches to government-sponsored space launches is an indication of the importance of outer space as both a corridor of transport and location of resources.

The recent few years have seen a rather curious interest in the perception of outer space. Whereas in the early years of outer space exploration, governments were the primary driver, a slow transformation has been occurring. In the modern era both payload developers and launch vehicle providers are becoming more commercialized. The recent phenomena and popularity of space tourism is one such case.

However, outer space still possesses a mythos about itself separate from any other type of environment. Outer space is at the nexus with our known terrestrial boundaries and thus projects a physiological lure driving human exploration initiatives. Humans have a general unease or relentless wherein the human condition dictates a drive to explore and go beyond currently known boundaries. Every such exploration
endeavor will always look to the next journey to be taken, the next frontier to explore. Thus as one initiative is concluding, decisions will need to made as to the next milestone in the process of exploration.

Various motivations are at the foundation of this quest for discovery. Intellectual, political, and monetary rewards have beckoned many explorers in history to push the bounds of human knowledge about the world. The justification of what to explore and how to explore are not based on engineering calculations or simple curiosity. Combinations of both motivation and constituencies available to allocate resources emerge to push such programs of exploration.

**MOTIVATION**

This examination will focus on what are termed here “mega-scale” projects in the specific domain of outer space. Mega-scale projects are loosely defined as large scale, longer term (ten years or longer), resource intensive (in terms of public outlay, program life cycle cost, labor requirements, etc.) projects societies initiate for various scientific, political, or economic rationales. Mega-scale projects are very difficult to complete, requiring coordination amongst multiple groups within societies and have a large involvement of government entities. Examples of mega-scale projects include the United States Apollo Space program, Space Shuttle, trans-continental pipelines, and large hydroelectric projects. Outer space specific mega-scale projects are examined here.

Many times mega-scale projects are both government funded and directed. Given the enormity of such projects, governments are the only willing actors to initiate such ventures. Commercial involvement occurs after such projects are initially developed, but not at the outset. Subsequently, the priorities of such projects are not based upon lone economic considerations.

Multi-dimensional challenges exist in mega-scale projects. This report tries to present a broad perspective on the problem of getting such projects initiated. Various areas of motivation are covered. Combined with such motivations are disparate constituencies, each interested in mega-scale projects for their own utility.

Generally, societies have opportunities where decision need to made as what types of mega-scale projects to develop. The United States and general international space community have such a decision point arriving in the latter half of this decade. Epochs defined by the mega-scale projects have marked the space age. Examples include the Apollo program, the Space Shuttle, and the International Space Station (ISS).

At this end of this first decade of the twenty-first century, the ISS will most likely be fully assembled and almost fully operational. NASA’s Space Shuttle and Russian expendable vehicles will be available for human transport to Low Earth Orbit (LEO). Expendable launch vehicles from all around the world will be available for government and commercial clients. Nascent Reusable Launch Vehicles (RLVs) may be appearing as smaller scale prototypes. Semi reusable systems may be on the verge of operation. Mars exploration will continue with several extended stay rovers, sample return missions to comets will continue, next generation space telescopes will be ready for deployment, and outer planets missions with advanced propulsion systems may be ready for launch. In such an environment, the international space community will have to examine the next large-scale coordinated project, the next logical step after the ISS.

This examination specifically focuses upon Space Solar Power (SSP) as a sample mega-scale project. SSP will be analyzed as a case study of some of the marketing potential for such a mega-scale projects. SSP was chosen since it is a large space project, possibly involves major government funding and/or regulation, involves multiple technology development programs, involves diverse and global various constituencies, and due to the availability of previous economic analyses for such a project.

The conclusions reached here do not argue that SSP is the only viable project that should be pursued by world governments and commercial industry versus any other space endeavor. The philosophy taken here is that if one is interested in pushing SSP as a mega-scale space project, how should such a proposal be marketed to the general community at large. The purpose here is to offer a systematic perspective on how to market a mega-scale project.
Various marketing notions are presented here that can be taken forward when implementation and development of such a project begins. Future analyses can examine more constituencies, the proper roles to target them to accept such projects, and methods to coordinate various groups together.

This study does not denigrate all previous studies of SSP but attempts to formulate some strategies given the outcomes of past reports. These studies include the later 1970s and late 1990s studies performed by NASA of SSP\textsuperscript{1,2,3}. Generally many of these studies take as their evaluation metric either engineering performance or financial price based parameters. This study does not calculate the gross mass of an SSP station or calculate the $/kW$-hr to be charged in the world energy markets; these metrics are not the totality of prime discriminators as to whether a program gets initiated. As a corollary, many of the analyses show SSP to be a very massive system with non-competitive market prices even when accounting for the price of pollution for various energy sources. Just as with all engineering problems, there are no utopian low mass and price SSP architectures.

**Reasons for Space Exploration**

Various motivations exist by the Earth’s culture for space exploration. A simple systematic breakdown yields three possible reasons; labeled here as intellectual (scientific/technology), crass (economic), and intrinsic (politics/culture) motivations. For this examination these three are informally referred to as “Mind”, “Body” and “Soul” motivating factors. This list is not meant to be exhaustive or complete but a means to be used as a starting point for discussion on this matter. One motivation, intrinsic, can be sufficient to carry out these programs, whereas the other two by themselves may not be (this is specific to space exploration). For example commercial telecommunications satellite markets stand partly on the foundation of government investment on both technologies on these payloads and the launch vehicles used to get them to orbit. These motivations also work differently in regards to the scale of the project. On a small scale, crass justifications may be sufficient to initiate a project; on a larger (mega) scale this may not make sense. In addition, for each motivation government plays varying parts; it can push based on some and not care about others.

**Reasons of the Mind**

One of the three reasons for exploration cited here includes intellectual motivation; the development of both general science knowledge and the development of new technologies. Specifically this can include discovery about the solar system, the origins of life, or the weather patterns on earth. This motivation also includes the drive for research and development of new processes and materials that can be applied both in space and terrestrially. Governments have substantial interest in this type of motivation and are clear proponents of the philosophy.

**Reasons of the Body**

Another motivation cited here includes the crass motivation of commercial, financial reward. This motivation should not be viewed as socially objectionable. Financial rewards drive many new initiatives and work similarly in space. Given the end of the Cold War space race, space commerce and commercialization are making their effects felt. Governments are attempting to entice more commercialization; finding synergies with public space exploration.

**Reasons of the Soul**

The final motivation listed here is an internal motivation referred to as intrinsic. This includes the human desire evident throughout history of pure exploration and subsequent colonization. Additionally, societal and cultural values are involved in this motivation. These motivations include the need to act against rivals or showcase a society’s scientific and military strength (national pride, militarization of space). It could also include the need to work cooperatively with other nations. Governments sometimes control these motivations of their populace (the Cold War) and sometimes are led (space tourism).

**Potential Mega-Scale Space Projects**

For the previously cited decision points coming up later on at the end of this decade, various mega-scale space projects could be initiated based upon the elements of space exploration (see Figure 1). These include continuation of a human space presence, evolvement of sample return missions, or...
telecommunications infrastructure development to name a few. One of the most vocal constituencies is arguing for more Human Exploration and Development of Space (HEDS) activities as a follow on to the ISS. Such ventures are more exclusive government domains and thus not chosen as the example mega-scale projects. Some of these projects are based on a combination of the three general types of motivation stated in the previous section.

**Figure 1. Sample Elements of Space Exploration**

The development of cheaper and safer reusable space transportation launch services was also not examined as mega-scale space project. Lower launch prices enable easier implementation of such projects. Such space transportation projects themselves are expensive, costing billions of dollars in vehicle development and acquisition. It was assumed that such development would continue regardless of any mega-scale space project. However, given the limitations of public outlays, two such simultaneous programs are interconnected. A terrestrial analogy would be the continuous improvement of highway roads regardless of the payloads being carried on them or the cities that connect to them.

**HEDS**

Human Exploration and Development of Space (HEDS) is a designation, often used by NASA, for current (Space Shuttle, ISS) and future space exploration initiatives. These projects specifically involve the human element but are coupled with complementary robotic exploration (see Figure 2). Sample HEDS missions include moon colonization, the first Mars mission, missions to nearby asteroids, or infrastructure development at Lagrangian orbital points (see Figure 3). The architectures involved are vast and are composed of various in-space transfer vehicles (solar, nuclear) and infrastructure nodes (orbital, surface). Specific HEDS objectives include:

- Explore the Space Frontier
- Enable Humans to Live and Work Permanently in Space
- Enable the Commercial Development of Space
- Share the Experience and Benefits of Discovery

Generally these missions can be seen as a continuation of the dreams of the public/government space program, a direct continuation of Space Shuttle and ISS programs.

**Figure 2. HEDS Roadmap**

**Figure 3. HEDS Mission Images**

**Space Solar Power (SSP)**

Space Solar Power (SSP) for terrestrial use is a concept to beam energy from space to terrestrial power grids that could be feasible in about twenty to forty years (see Figures 4, 5, and 6). In theory, due to negligible atmospheric losses, power generation from solar cells in space is nine times as efficient as on the ground. SSP would harness these efficiencies through technologies such as microwave wireless power transmission (WPT) to large (several kilometers in diameter) terrestrial rectifying antennas (rectennas) for eventual dispersion into the power grids of the world (see Figure 7). Extensions of the SSP concept include use as an in-space power source for multiple...
locations around Earth and within the solar system (Mars).

Markets for potential use of SSP services are global in nature. Thus the ground infrastructure may have to be as well. Developing countries, where general electricity prices are higher, may be possible locations of such rectennas. SSP is in essence a space infrastructure development project whose initial capabilities may be demonstrated for terrestrial use.

A sample SSP architecture incarnation, the Geostationary Earth Orbit (GEO) SunTower, would deliver about 1.2 GW of power to a terrestrial electrical grid, having a total system mass of over 20,000 MT (equivalent to more than 40 International Space Stations) and each lasting over 30 years in orbit (see Figure 8).

Each Solar Power Satellite (SPS) would have its operational life be in GEO and be constructed from smaller pieces typically delivered from Low Earth Orbit (LEO). A dual phase transportation system emerges from this scenario, namely separate Earth-to-Orbit and in-space transportation modes. In this
envisioned scenario, an RLV delivers a 20-40 MT piece of the SPS to LEO which is either sent directly with the in-space “tug” to the final orbit in GEO or aggregated with previously delivered RLV pieces into a “wagon train” in-space transportation system to GEO\(^4\). This delivery schedule would be kept in order to assemble one SPS in orbit for over 30 years.

Dr. Peter Glaser first proposed Solar Power Satellites (SPS) in 1968 with NASA and the Department of Energy (DOE) of the United States (U.S.) eventually conducting its own feasibility study\(^5\). Ever since the energy scarcity created by the oil shocks in 1970s, solar energy has been regarded as a significant alternative energy source\(^6\). In 1978, the Sunset Energy Council was set up in the U.S., consisting of private entities and scientific institutes (including MIT, Arthur D. Little, Boeing, Martin Marietta, McDonnell Douglas, General Electric, RCA Grumman, Avco Corp, Westinghouse, Southern California Edison, and Aetna Life and Casualty Insurance Co.). This resulted in a bill to provide for a research, development, and demonstration program to determine the feasibility of collecting space solar energy to be transmitted to Earth and to generate electricity for domestic purposes (H.R.12505). This 1979 Reference Study resulted in a “Battlestar Galactica” type architecture (cost to first power greater than $250B), needing more than 500 astronauts for orbital construction of 60 satellites delivering over one GW of power to ground stations.

In 1997, NASA concluded the “Fresh Look” Study resulting in various configurations including the SunTower\(^1\). This led to other SSP concept definition studies and eventually to an increased budget of $20 million for the SSP Exploratory Research and Technology (SERT) program in 1999; being conducted with representatives from Japan, the European Union (EU) and Canada. Due to the current climate of limited public funding for such large-scale, non-defense oriented space projects; the governments of the world would prefer more industry involvement (technically and more important financially) in SSP.

A future SSP mega-scale project could consist of various organizational forms including: International governmental organization (IGOs), International non-governmental organizations (NGOs), or Multinational enterprises. Each of the basic three organizational types has many offshoots, including types that are domestic or transnational. Several example structures that arise out of the basic three types include:

- Civil government consortium: International Space Station (ISS) agreements with each country having jurisdiction over own portion of station within international regulatory agreement
- Commercial consortium: International Launch Services (ILS) organization of multiple companies from multiple nations with various marketing, production, and operational locations
- Commercial organizations: Boeing having national and international contracts with both other international companies (GE) and other countries (defense sales)
- Public/private organization: Arianespace’s public funding of various developments but also pursuing commercial customers for its products and transitioning from government funding to more commercial financing

Previous economic analyses have indicated that a fully commercialized SSP system for terrestrial use will not be viable due to the incremental profit compared to massive up-front investment cost and project risk\(^7,8,9\). For clarity, the “fully” commercial project as defined above would obtain minimal government assistance for program research and development (as well as system acquisition), not receive any government subsidized loans, not receive any government tax breaks, not receive any government liability waivers, not receive any free spectrum for transmission purposes, or benefit from pollution taxes on competing sources of power.

![Image](http://example.com/image.png)

**Figure 9. NPV For SSP Organizational Types**
Probabilistic analysis of potential SSP commercial companies indicates that there is not sufficient financial justification to pursue such projects\textsuperscript{10}. Figure 9 displays a comparison of the Net Present Value (NPV) of three types of SSP organizations: IGO, NGO, and fully commercial. The NPV is a financial metric indicative of a commercial project’s value given discounted cash flow (DCF) analysis using a discount rate that is reflective of the risk of the project. A higher NPV is a sign of a much more financially worthwhile project. The results for all three types show a negative NPV, indicative of the difficulty in making the SSP business case close.

**POSITIONING THE SCIENCE**

SSP as an architecture consists of multiple elements. Each of these elements is predicated upon technology development. Previous studies of SSP have indicated that many areas of technologies will have to be developed in order to make SSP even technically feasible. Technology challenges could include:

- Mass Producible Systems
- High Modularity Systems
- High Temperature Superconducting Cables
- Rigidized Hoyt Tether
- Intelligent Modular Systems
- Higher Efficiency Photo-Voltaic Arrays
- Thin Film/Inflatable Structures
- Mass Producible Arrays
- Highly Modular Systems
- Electrodynamics Tether Propulsion
- High Efficiency Electric Thrusters
- Highly Reusable Vehicles
- Robotic/Self Assembling Systems
- Autonomous Rendezvous/Docking
- Wireless Power Cost Phase Shifters
- Low Mass Phased Array
- High Temperature/Passive Thermal Management
- High Efficiency Rectenna
- Rectenna Fail Safe Beam Pointing/Control
- Autonomous Operations
- Low Cost High Energy Storage
- Debris-Impact Tolerant Systems
- Low Hardware Refurbishment Per Decade

Generally many of these technologies (perhaps besides those for wireless power transmission) are similar to those used to enable HEDS-type missions. However more emphasis is placed on solar cell development for SSP than potential nuclear propulsion initiatives (that would encourage HEDS missions). SSP has synergy with terrestrial solar cell development. Given the modular nature of currently envisioned architectures, robotics and orbital operations play a key part for SSP feasibility. The development of such operational technology and experience could have direct benefits to commercial satellites deployed in orbit. Technologies for SSP can more closely aligned with terrestrial technologies and thus the potential exists to align the benefits to terrestrial constituencies.

**POSITIONING THE ECONOMICS**

SSP may not be a rational pure financial investment, but relative to other mega-scale projects it is more appealing. As seen in the previous section, given current assumptions about technology development, a purely commercial justification for SSP may not be available. However, this is possibly also true (or even worse) for many of the other mega-scale space projects. HEDS initiatives are not closely aligned as SSP is to the commercial sector. SSP mega-scale projects do not involve science gathering for their own sake. The ultimate customers for SSP are not Principal Investigators (PIs) at universities around the world. SSP is focusing on providing a commoditized product to the underserved customers of the world.

SSP is an infrastructure development project akin to other projects such as hydroelectric dams or natural gas power plants. The location of the infrastructure is a major difference (technically and psychologically). As an infrastructure development project, the targeted consumers may not be countries financing the development but countries that desperately need the output energy (i.e. developing nations).

In providing energy to underserved niche markets (where higher prices can be charged relative to developed countries), SSP may be a better way to sustain development. Given the increasing population of countries such as China, India, Pakistan, Nigeria, etc. the path of sustainable development probably should not follow the path of current industrialized countries. Current terrestrial resources may not be sufficient to handle such a massive wave of consumption. First world consumption patterns may in the end not be a sustainable model for these growing countries. SSP could be positioned as a
concept to help develop alternative models of sustainable development (in terms of providing energy) to these developing nations.

**POSITIONING THE POLITICS**

SSP in terms of an infrastructure cannot compete with the adventurous notions of a human mission to Mars. However, the day-to-day political implications of infrastructure projects are greater than single exploration missions. SSP can be positioned to deal with various issues arising out of global warming, alleviate global energy crises, assist in international space cooperation, work with non-space institutions for general development, and integrate government space spending more efficiently with the commercial marketplace than other mega-scale space projects.

In terms of demand, both worldwide population and per capita energy consumption are increasing, and will double in next twenty years and double again twenty years after that. In terms of the environment, consensus may be reaching that there is some type of change occurring but the impact may be unknown (see Figures 10, 11, and 12).

**Figure 10. Short Term Global Temperature Profile**

**Figure 11. Long Term Global Temperature Profile**

**Figure 12. Historical Global Atmospheric Content**

Given this history, alternatives are being examined that can simultaneously meet energy demand and are not implicated in various global weather change phenomena. Specific potential alternative paths include:

- Reduce Demand (Energy Efficiency)
- Biomass
- Wind
- Nuclear (Fission and Fusion)
- Hydroelectric
- Hydrothermal
- Solar (Terrestrial Solar and Space Solar Power)

SSP can be seen as a part of the solution to these energy demand and pollution issues. Obviously SSP is not a completely environmentally friendly architecture (solar cell development and rocket plume exhaust are notable examples). However in relative comparison with other sources, and the affiliation of the word “solar” with this energy source, make it seem relatively clean.

There is always concern about long-term supply of oil to meet worldwide demand. Recently, particularly in the United States, there is more concern about the actual sources of oil and dependence on once assured countries of production (i.e. Saudi Arabia). SSP can be viewed as a potential energy option available to developed countries for alternative sources of energy not reliant on a foreign supplier. Simultaneously such a program would help the domestic space services industry.

The large scope of any SSP architecture (in terms of development and more specifically operations)
necessitates using the resources of multiple nations. The ISS can be seen as an initial model for future international development projects. The SSP architecture, with various recetennas positioned in different locations actually has internationalism imbedded in the architecture. SSP could be positioned as a better follow-on project to the ISS since multiple types of domestic entities (space, power, etc) would have to coordinate with their international counterparts. An example of recent developed and developing country coordination include Surrey Satellite’s constellation initiative for third world countries.

SSP could entail involvement by international development organizations that traditionally do not participate in the space arena. SSP, in essence a development project, could partner with non-space institutions (U.N., World Bank, International Monetary Fund-IMF, etc.). Such relationships would provide needed economic offsets to make SSP viable. In addition, SSP can position itself as similar to any other type of internal development project, helping to negate its impression as a completely foreign type of project and enlarging the alliance of supporters.

SSP is also a mega-space project where the transition to a commercial or semi-commercial entity to operate the facility after construction could be easily imagined. This is unlike other types of projects, such as the ISS, where the commercial operator’s goal is science development. Subsequently, a better model for the ISS may consist of some type of private, non-profit operator. Commercial energy providers may be willing to become SSP operators, and bring the same efficiencies as in terrestrial energy production facilities.

Space exploration is many times seen as irrelevant to the condition of the populace of the planet from which the money comes for such projects. When in this new century, billions of people on the planet still have never made a phone call or even have access to clean water, the origins of this skepticism can be understandable.

Through positioning itself as more of a development project SSP can add alliances with powerful, non-space related organizations. SSP generally can count on attracting a base constituency arising out of the space industry. The problem with many such space projects involves the underdevelopment of non-space constituencies. Many times non-space groups are more vocal and diverse than mainline space interest groups such as the Mars Society or Planetary Society, whose causes are more diverse and broad in which they essentially act as nebulous “exploration” caucuses. For mega-scale space infrastructure projects, the less space-oriented a project seems and the more non-space constituencies support it, the better likelihood of ultimate public funding. Support amongst non-space advocates may also have a recurring effect of reinforcing support amongst the base space constituency. In addition, the political support of multiple, broad alliances will assist in sustained support of such projects over time. The successful implementation of mega-scale space projects will require coordinating the motivations and networking the influences of large and diverse constituencies.

REFERENCES


