Sunrise in Orbit

Sunrise in Orbit - A Policy Roadmap for Space Solar Power

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Executive Summary

Space solar power (SSP) is a method of collecting solar energy with a satellite and beaming it to a receiver, either on Earth or in space. Initial power beaming capabilities have been demonstrated, and multiple countries and commercial companies are actively pursuing SSP projects, both independently and collaboratively. Motives for development of SSP capabilities may include securing sovereign launch capabilities, energy independence, achieving Net Zero carbon emissions, and job creation.

SSP will generate spin-off dividends, as it drives innovation in a range of component technologies. These include photovoltaics, advanced solar panel and blanket technologies, advanced solar array technologies, robotics and automation, orbital debris removal technologies, advanced cooling and thermal management, and power beaming, among others. Construction of a SSP array will also push forward other space industrial capabilities, such in-space servicing, assembly, and manufacturing and in-situ resource utilization.

This paper offers a policy roadmap to a United States SSP project. It identifies key issues that may be resolved in order for the United States to take advantage of this opportune moment. First among these is choice of architecture, as several designs for the SSP array have been suggested. Second is spectrum allocation, which could take nearly a decade to attain. Third, an agency must take the lead in developing SSP. Space solar power is technologically feasible and is already developed to the point where it may return investments threefold.

First Principles

- Space solar power may be beamed space-to-space or space-to-earth
- Space solar power may be beamed with multiple methods:
    - Microwave/RF
    - Lasers
    - Space-based reflectors
- Initial space-to-space and space-to-ground power beaming have been demonstrated
- Multiple countries are actively pursuing both independent and collaborative space solar power projects
- Commercial companies are actively pursuing space solar power projects
- Development of space solar power will produce spin-off benefits
- Motives for development of space solar power capabilities may include:
    - Securing sovereign launch capabilities
    - Energy independence
    - Achieving Net Zero carbon emissions
    - Job creation

Introduction

The concept of collecting solar energy in space and beaming it to Earth via wireless power transmission is now a century old. Konstantin Tsiolkovsky proposed in 1923 that space-based mirrors could beam sunlight to the ground. [1]. In 1941, Isaac Asimov published a short story, “Reason,” set on a solar power satellite that beamed energy around the solar system. [2]. The first patent for a solar power satellite, issued in 1973, went to Dr. Peter Glaser, who went on to perform several studies on space solar power for the National Aeronautics and Space Administration (NASA).

The 1974 NASA feasibility study laid the foundation for future SSP studies. [3]. It determined radio frequency to be the best method for power beaming, examined spectrum allocation issues, proposed rectenna site selection criteria, and estimated power output, mass, material, and load lift costs. The Glaser study assumed 25 million pounds for the array and 30,000 pounds of propellant per year, \$2.5B (\$15.45B in 2023) for a 5000 kW system, gallium arsenide solar cells at 18% efficiency, an overall efficiency rate of 70%, and a 30-year lifespan. The study predicted that “by 2001 the annual U.S. demand for energy in all forms will double and the annual world-wide demand will probably triple.” Increased energy demands created a key rationale for the SSP project. [3].

In 2022, the European Space Agency (ESA) commissioned two feasibility studies. The Frazer-Nash study, commissioned by the UK government, “assumes that a European SBSP will not be developed without public sector intervention” and that electricity demand in Europe will increase by about one-third by 2050. [4]. It proposes a ten-year construction schedule, requiring two years per satellite, and compares this development period with that required to design, build, and deploy Starlink. Using the CASSIOPeiA architecture, the study estimates at least a 15-year lifespan which could be extended by replenishing modules with newer-generation subsystems. This system would provide full coverage of Europe, with 6,500 suitable rectenna sites identified in France, Germany, Italy, Poland, and the UK. The scale of such a project would spur development of “fully sovereign super-heavy lift launch capability” in Europe. [4].

In January 2024, NASA released its most recent study on space solar power, stating in the first paragraph that “it is generally understood that SBSP is cost prohibitive and technically infeasible today” and using 2050 as its target date. [5]. The study compared two architectures, referred to as “Innovative Heliostat Swarm” or RD1 and based on SPS-ALPHA Mark III, and a “Mature Planar Array” or RD2, similar to the Tethered-SPS design proposed by JAXA; the study did not include CASSIOPeiA, the design proposed by ESA. [6], [7]. This study compared the LCOE of space solar power with that of nuclear fission, geothermal, hydroelectric, utility-scale solar photovoltaics with storage, and land wind without storage. Cost estimates included launches with single-use Starships and $38.9B for decommissioning the array out of geostationary orbit after only a ten-year projected lifespan. The 2024 NASA report suggested continued monitoring of developments in external projects relating to space solar power, including power beaming. [5].

The Path Forward – Intermediate Milestones

Much of the past research on space solar power (SSP) has focused on the visionary dream of a future in which SSP drastically changes the world. Space solar power offers the possibility for civilization changing effects from the successful implementation of a large-scale system, and this view provides a useful view of the prospective future. However, an incremental approach is critical in achieving SSP, simply because the end goal is so complex, and there are many necessary steps in between current systems and a SSP system capable of providing firm dispatchable power. Space solar power will require maturation of current technology and many significant demonstrations. Continuing to work in the same direction without stopping to evaluate progress perpetuates a cycle of thinking that inhibits forward momentum on SSP. An incremental approach that allows for demonstrations of the technology along the way will also be critical in developing public trust on an issue that has already been marked by controversy and polarization. This section seeks to identify incremental milestones to be achieved on the way to the civilization changing end goal of SSP, including capabilities that each step could demonstrate.

Ground-to-Ground Power Transmission

The logical first step on the path to achieving firm dispatchable power provided by SSP is the development of ground-to-ground technologies for power beaming. Several companies are already working on these technologies for a variety of applications. One notable example is EMROD, whose work in long range wireless power transfer is on the cutting edge of energy technologies. EMROD’s technology consists of a transmitting antenna and a receiving antenna, as well as relays that can help to refocus the beam and extend its range. [8]. EMROD is just one example of a handful of companies working on power beaming.

There are many useful applications of ground-to-ground long range wireless power transfer. Power beaming systems like EMROD's require much less infrastructure than traditional powerlines, making them a good solution for providing remote communities such as those found in Alaska where their primary source of power is diesel-fueled electric generators. [9]. Being able to provide power to remote communities that are not able to lay and maintain power lines would be greatly beneficial. Conversely, ground-to-ground long range wireless power transfer could be used to beam energy out of remote areas where wind and solar are most productive. Remote sources of renewable energy are often expensive to connect into the grid and underwater cables can be difficult to maintain. Not only does power beaming circumvent the need for underwater cables, but it could also be a cheaper and easier solution for connecting remote facilities to the rest of the grid. In more congested power markets, long interconnection ques and difficulty obtaining right of ways for transmission lines add to the challenge of connecting new renewable energy to the grid.

Making advancements in ground-to-ground applications of power beaming technologies not only provides the opportunity to demonstrate capabilities that can later be applied in-space, but it also allows for the maturation of the technology, making it more reliable, and driving down the cost. Advancing ground-based power beaming capabilities will also provide a more accessible and less costly environment for researchers to test and iterate technologies allowing them to improve efficiency before moving to the more costly and complex challenges related to space-based applications. Ground based applications could also provide an early market for component suppliers to sustain their business before a full SSP system is begun. Starting with ground-based applications will come with the added benefit of helping to establish regulatory frameworks and build public trust early on so that the process of integrating SSP later can be streamlined.

Air-to-Ground Power Transmission

Following ground-to-ground, air-to-ground applications of power beaming technologies are a good next step in an incremental approach to achieving SSP. It would allow for the testing of new components, such as dynamic beam steering and phased arrays, that may not be necessary for ground-based applications, while allowing for the further maturation of the technology, still without having to incur the increased cost and complexity of space-to-space applications.

Drones are a prime example of how air-to-ground power beaming can be applied. By utilizing ground stations to transmit energy to a drone, its flight duration could be extended significantly allowing longer duration missions than is now possible. For the military, this could make drones more effective for surveillance and intelligence gathering by enabling them to fly continuously without having to stop for fuel or recharge, as well as allowing them to stay in highly remote or hostile areas where refueling is difficult. The advancement of this technology would also have benefits for humanitarian aid, enabling much more thorough and longer duration search and rescue efforts during natural disasters, and emergency response situations like plane crashes.

Like with ground-to-ground applications of power beaming, pursuing air-to-ground applications before moving onto space allows for further opportunities to demonstrate the capabilities of the technologies developed, and assess the progress that has been made, as well as allowing the technology to further mature before being applied to the harsher challenges of the space domain. There is also valuable operational experience to be gained from the air-to-ground applications of power beaming that may prove to be helpful in applying power beaming to SSP. The further development and deployment of power beaming infrastructure will help to drive down costs through economies of scale.

Space-to-Space Power Transmission

Space-to-space applications of power beaming technologies provide the logical first step for demonstration in the space domain. Space-to-space power beaming is a specific application that has already been demonstrated in a limited capacity and can provide immediate benefits. For example, the U.S. Naval Research Laboratory (NRL) has undertaken the Space Wireless Energy Laser Link (SWELL) project, successfully demonstrating space-to-space laser power beaming capabilities. [10]. Experiments like SWELL not only allow for demonstration of SSP systems, but also give scientists the opportunity to study the performance, efficiency, and degradation of power beaming systems in the space environment. This is one of the most critical steps on the path toward space-to-ground power beaming, as it will allow for further maturation of the technology and drive down the cost of SSP systems. [11].

The first step into the space domain will be critical to laying the groundwork for more complex SSP systems. Using SSP for satellite refueling operations could be an early application, leveraging the proximity of SSP satellites to provide a valuable service to existing satellites in need of refueling. This would demonstrate not only the technical feasibility but also the practicality of SSP for satellite servicing missions as well as showcasing its potential for broader applications.

Cislunar

As a follow on to the already demonstrated capability of space-to-space power beaming utilizing lasers, a good next step would be to pursue SSP for cislunar operations. According to one subject matter expert, space to lunar surface power beaming, particularly using lasers, is a very advantageous scenario to demonstrate space to surface power beaming. This could be particularly useful for providing energy to assets located in permanently shadowed lunar craters that receive no sunlight. It would also allow for energy to be supplied during the lunar night, which lasts roughly two weeks [12]. There is also the opportunity for further development of satellite servicing industries in cislunar space. As the human presence around the moon continues to grow, there will be a need for satellite refueling in lunar orbits. Additionally, SSP systems in cislunar space could also provide refueling services to communications satellites in GEO. As communications satellites shrink, and constellations grow, so will the demand for refueling services in the satellite communications market, giving SSP providers the opportunity to demonstrate the value of SSP.

The new information gleaned from larger scale space-to-lunar surface power beaming will be extremely valuable when moving toward space-to-ground power beaming. Not only will it provide opportunities to demonstrate space-to-ground capabilities on the Moon before turning SSP systems toward the Earth, but it will also further mature critical technologies, drive down cost, and potentially have already started to make SSP profitable.

Beyond the benefits to SSP specifically, pursuing activities in cislunar space will serve to reinforce the position of the United States as the leading spacefaring nation, and ensure that the US can compete with China, who has already signaled their intention to dominate cislunar space. [13]. During the space race, the U.S. was victorious because of the success of the 1969 moon landing. Now, victory in competition between the great powers will again likely be determined by success in cislunar space. With the recent completion of the Chinese Tiangong space station, and no current plan for maintaining a constant human presence in space beyond the decommissioning of the ISS, the US risks losing prestige and its international standing as the leading spacefaring nation. This makes cislunar space a critical domain both for the advancement of SSP, and interests of the U.S. at large.

Space-to-Ground

The last step in this approach is space-to-ground power beaming. Within this area there are several applications that could allow for SSP to be scaled up to the point that it can provide firm dispatchable power. The first of these applications involve the use of portable rectennas for providing humanitarian aid and disaster relief. With a portable rectenna that can be moved and set up anywhere, it would be possible to provide humanitarian aid to other countries in the form of backup electrical power. This could come in several forms including providing energy to power hospitals in regions facing an epidemic, water purification, and sanitation efforts. There is also the opportunity for SSP to be used in disaster relief. When recovering from a natural disaster, the three factors play a determinant role in how costly recovery efforts are: energy, illumination at night, and communications. [14]. The longer it takes to restore these critical services, the more costly recovery from natural disasters becomes. According to the National Oceanic and Atmospheric Administration, since 1980, hurricanes alone have caused over $1.3 trillion in damage. [15]. Just in the US in 2017, 16 weather related natural disasters caused $306.2 billion in damage. [15]. With portable rectennas able to help disaster-stricken communities recover faster, the approximately $22.8 billion per event price tag could be significantly reduced, saving money in both recovery costs and the loss of GDP following disaster situations like the $60 billion cut the US's GDP in the second half of 2006 following Hurricane Katrina. [14].

Space-to-ground power beaming has the potential to be beneficial for both civilian and military purposes. For the military, a prominent use case for SSP is providing energy to forward operating bases. Due to their often-remote locations fuel must be transported to forward operating bases both increasing the cost of providing them energy and making the transports the target of hostile forces. These issues could be minimized using SSP. [16].

Agriculture represents a potential application for civilian use of SSP. According to the Center for American Progress, "The only sector that appears to be uniquely rural in nature is agriculture, which accounts for nearly 17 percent of employment in highly rural and remote areas.” [17]. Rural communities are often more heavily affected by power outages, and this can cause major disruptions for agricultural operations. [18]. SSP can also be beneficial in providing uninterrupted power in these rural and remote areas. It also has the added benefit of decreasing the heavy reliance on fossil fuels in the agricultural industry. [19].

SSP can be incredibly beneficial in improving grid resiliency on the path to baseload power. Because SSP would not rely on existing terrestrial infrastructure, it could act as a safeguard, continuing to provide power, and mitigate the negative effects of grid failure during disaster events such as the Texas grid failure in 2021 during which a severe winter weather event left eleven million without power some for up to three days, and resulted in the deaths of 246 people. [20], [21]. Because SSP is not affected by severe weather events that can have an impact on terrestrial energy infrastructure, it can support grid resilience helping to maintain power supply during severe weather events like hurricanes and winter storms that pose a significant risk to traditional infrastructure and serve as a redundancy for other critical infrastructure such as hospitals during times of grid failure.

The last milestone on the path of SSP is the capability to provide baseload or firm dispatchable power. In contrast to other renewables like solar that are restricted by weather and the day/night cycle or wind and hydro that are only feasible in certain locations, SSP would be able to provide a continuous source of energy without environmental restrictions. SSP also outperforms other sources of renewable energy in land use. According to the National Space Society, for “an SSP system to deliver 10 Gigawatts of baseload power at an average of 100 Watts per square meter to the rectenna would cover a ground area of about 36 square miles. In comparison, 10 GW of baseload power delivered by ground solar power would require a solar array covering about 360 square miles, after accounting for nighttime, seasonal variations in solar intensity, spacing of the solar collectors, and the effects of clouds and other weather conditions. This is 10 times as much area as the SSP requirement.” [22].

While there are other potential sources of carbon-free baseload power, they face challenges that could make SSP the best option. Hydroelectric power is geographically constrained and has already been implemented in the most ideal locations, and nuclear power faces hefty costs for wider implementation on top of significant public opposition. New implementations of geothermal electricity generation are emerging, but they are also geographically restricted and disruptive to the land.

Batteries are being examined for firm dispatchable power, but the cost/duration tradeoff is challenging. Carbon capture and storage could allow some fossil fuel use for firm power up to the 2050 net zero goals, but the technology is expensive and unproven. Each existing source of carbon-free firm power has significant trade-offs and to hit the goals of the Paris Agreement, it will likely take a portfolio approach, including SSP.

Even within the category of space-to-ground SSP applications there are several opportunities to demonstrate and advance different capabilities of SSP from portable rectennas, to the usefulness of SSP in both civilian and military applications, and the implementation of SSP for grid resilience that is scalable to baseload power supply. These all create opportunities to make SSP more economically viable, drive down costs, and mature existing technologies.

Exit Ramps

At each of these stages of implementation, there are viable exit ramps that allow for the pursuit of the visionary goal of SSP while benefiting other priorities and sectors. At the ground-to-ground stage of development, exit ramps could include a pivot solely to terrestrial applications of power beaming technologies such as wireless power transmission. Air-to-ground exit ramps could include transitioning to more immediately commercially viable applications like providing continuous power to high-altitude platforms and drones for both civilian and military purposes. Exit ramps that could come from space-to-space applications include satellite servicing and refueling, an application that is already likely to come out of current work on SSP. Exit ramps at the cislunar application stage could include power beaming to the lunar surface as well as providing support for exploration and deep-space missions. Even at the point of achieving space-to-ground power transmission, there are potential exit ramps including more limited use for powering forward operating bases, disaster relief efforts, or providing power to individual industries such as mining and data storage.

The Roadmap

1. Spectrum
2. International Cooperation
3. Commercial/Public-Private Partnership
4. Liability
5. Orbital Debris
6. Health and Safety
7. Public Engagement
8. A vision without a voice

The Roadmap

1. Spectrum

A critical issue in implementing space solar power systems is the selection of wireless power transmission frequency. This issue has technical, economic, and policy dimensions. The selection of frequency will impact the efficiency of transmission through the atmosphere (for space-to-ground applications), the size of the transmitters and receiving antennas, and interference of the selected frequency with other applications in adjacent spectrum bands, as well as maturity level of required components. Economic implications include the price competitiveness of a selected band of spectrum and the marginal profitability of the energy produced from a space solar power satellite compared to alternative uses of that spectrum band. Policy implications include the selection and availability of frequency bands and competing uses including various wireless communications technologies, such as broadcasting, cellular phone, military, and public safety system networks operating in that band. This section will address only the policy challenges for frequency allocation, given the thorough coverage of technical challenges addressed elsewhere.

The choice of electromagnetic frequency used for power beaming from space has important policy and operational implications. Both radio frequency and laser power beaming have been proposed. While laser power beaming provides the advantage of a smaller ground receiver size and would not cause harmful interference with existing telecommunications infrastructure, the components needed are less mature and more power is wasted when transmitting through the atmosphere over long distances. Due to the lack of atmospheric attenuation, laser power beaming would be most useful in space-to-space applications, such as satellite refueling and beaming power to a lunar base.

Radio frequency power beaming is the most explored solution in past space solar power studies. This is the frequency range between 3 kHz and 300 GHz, with 2.5 GHz and 5.2 GHz being the most cited in SSP reports. There are technical tradeoffs to consider. The higher the frequency the smaller the ground receiver needed, however the atmospheric losses become significant past about 30 GHz. The maturity of the transmitter and receiver technology is also higher at lower frequencies, leading to a cost trade-off between higher performance and higher cost devices.

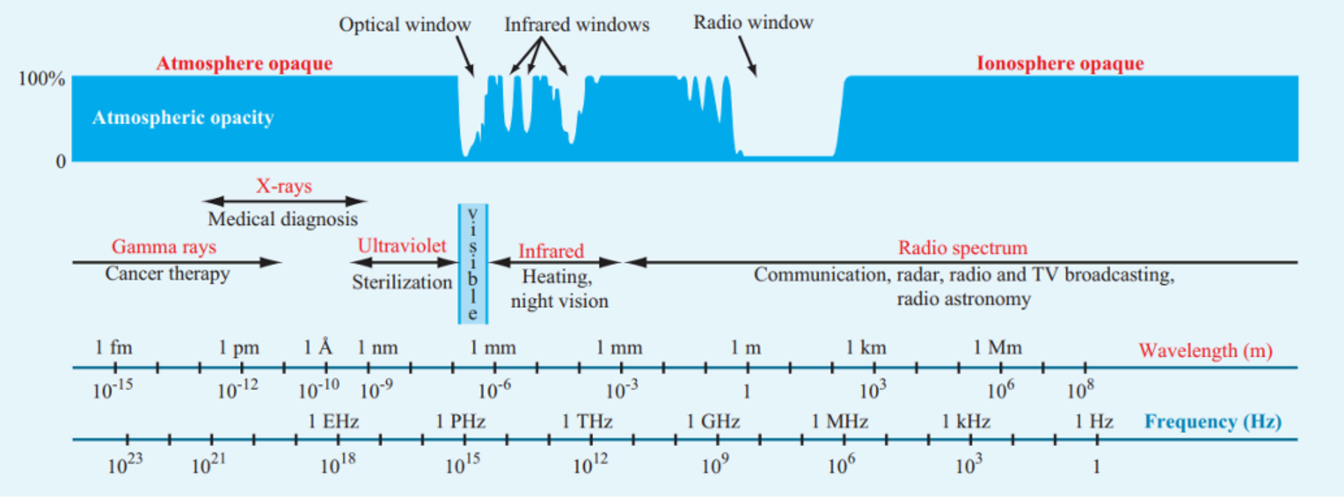

Figure 1: The electromagnetic spectrum including atmospheric transmission windows. (NASA 2024).

While the selection of which radio frequency band for a space solar power system is important for technical and efficiency reasons it is also critical when considering current laws and policies governing the use of the RF spectrum. Most importantly are three bodies – the Federal Communications Commission (FCC), the National Telecommunications Information Association (NTIA), and the International Telecommunications Union (ITU). These organizations govern the use of the RF spectrum in the U.S. (FCC & NTIA) and globally (ITU). Assigning spectrum for a space solar power project, whether public or commercial, will require dealing with these institutions, on their typical timeframe of operation and through their typical processes.

1.1. Federal Communications Commission (FCC)

The FCC is the U.S. government agency that regulates the use of radio frequency (RF) and administers spectrum for non-Federal use. It is divided into seven bureaus, two of which, the Space Bureau and the Wireless Telecommunication Bureau, are most relevant to space solar power. The Wireless Telecommunications Bureau is tasked with administering competitive auctions for RF spectrum and the Space Bureau is responsible for "leading policy and licensing matters related to satellite and space-based communications and activities." [23].

Private U.S. companies wishing to develop a space solar power satellite will need to bid on accessible spectrum bands in a competitive auction at the FCC. There have been over 100 competitive auctions since the FCC began holding them in 1994. [24]. Many SSP studies have assumed 2.5 GHz or 5.2 GHz spectrum. The 2.5 GHz band (which extends from 2496–2690 MHz) is the largest contiguous frequency band below 3 GHz and in the past has been dedicated to Educational Broadband Services and commercial Broadband Radio Services. Until 2021 it was largely unassigned in large parts of the United States but since then has been auctioned off for expanded 4G and 5G cellular coverage for tribal and rural communities. [25], [26]. The 5.2 GHz frequency band is used for long-distance radio telecommunications. [27].

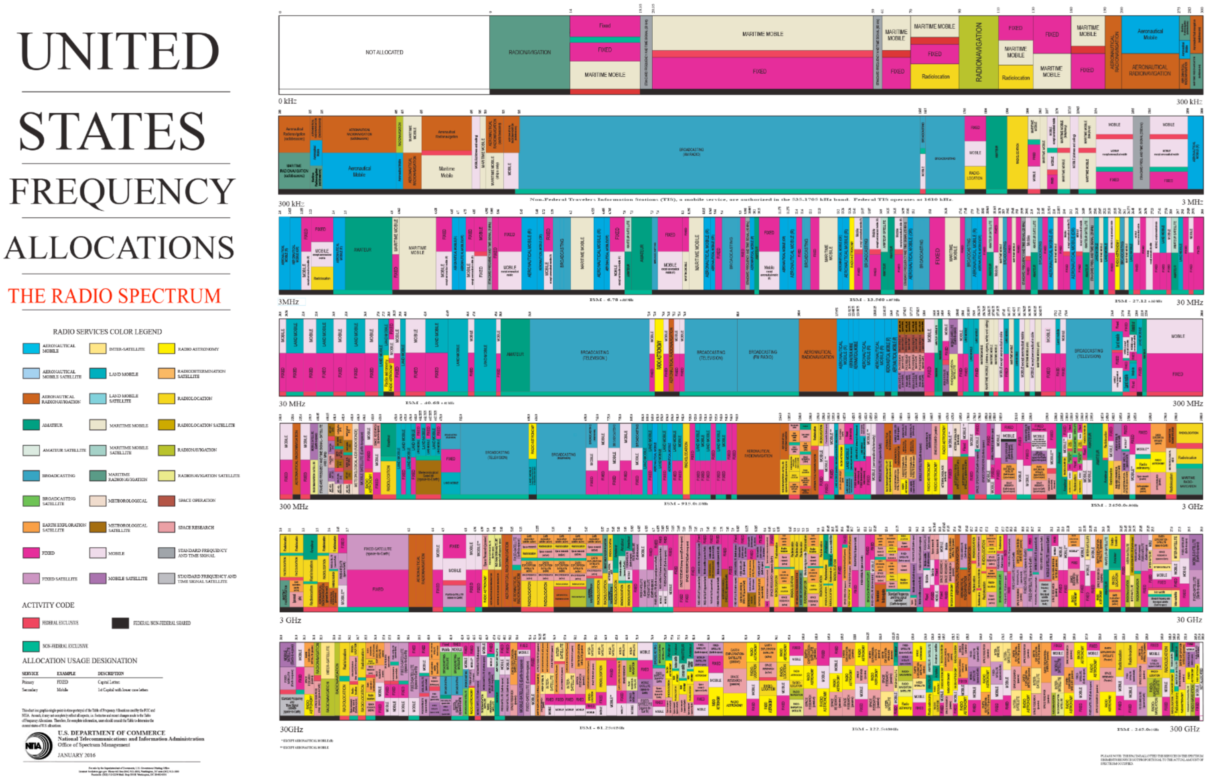

Figure 2: The Radio Spectrum - allocations of frequency bands for commercial and public uses. (Keegan 2023).

The process for obtaining the legal right to operate an RF system in a particular spectral band is important for space solar power systems to consider before investing large amounts of capital in demonstration projects. Maturing technology such as transmitters and rectennas that are most efficient in a particular band could be problematic if that band is sought after for high margin uses like cellular service or satellite data transmission, or if it overlaps with bands dedicated to existing national security or public safety uses. The competitive auctions run by the FCC and the likely costs of spectrum should be closely considered in any serious techno-economic analysis of space solar power and when determining the final design of such a system.

1.2. National Telecommunications Information Association (NTIA)

The U.S. executive branch agency in charge of spectrum allocation for the U.S. Federal government is the National Telecommunications and Information Administration, within the Commerce Department. NTIA is principally focused on “expanding broadband Internet access and adoption in America, expanding the use of spectrum by all users, and ensuring that the Internet remains an engine for continued innovation and economic growth.” [28]. In addition to expanding broadband access, internet security, online privacy, and copyright issues, NTIA manages “the Federal use of spectrum and identifying additional spectrum for commercial use”, which will impact the implementation of space solar power. For government sponsored space solar projects, working through NTIA will be an important step in allocating spectrum for an operational project. [28].

1.3. International Telecommunications Union (ITU)/World Radio Conference (WRC)

The International Telecommunications Union (ITU) is a specialized agency of the United Nations that plays a critical role in radio frequency spectrum allocation. As one of the longest running international, intergovernmental organizations, it predates the United Nations, having its origin in an 1865 meeting in Paris with twenty nations to coordinate the telegraph systems of Europe. [29]. Since then, the body has expanded its purview and consolidated with other coordinating bodies and includes 193 member countries and over 1000 companies. [30].

The ITU is critical to a future SSP project because its international role is to manage a formal and standardized regulatory process to facilitate the optimal use of a finite global resource – radio spectrum. Radio signals whose frequencies are too close can interfere with each other. Unregulated use of the radio spectrum would destroy the ability for anyone to successfully transmit signals using radio waves. The ITU sets aside specific bands for agreed upon use cases and requires individual radio users to register their use of specific wavelengths. The ITU’s Radio Regulation Board provides arbitration and formal review, ensuring consistency of application of conference decisions and the resolution of conflicting claims. [31].

The World Radio Conference is only held every three to four years. This is where the ITU meets to review and revise the Radio Regulations - the international treaty governing the use of the RF spectrum and satellite orbits. [32]. Revisions to the Radio Regulations are made based on the agenda developed through a lengthy preparatory process by the ITU Council. The scope of the agenda is determined four to six years in advance of the conference. [32]. The agenda is finalized by the ITU Council with the agreement of the members two years in advance of the next World Radio Conference. The ITU Council consists of 48 member states elected at the WRC and meets yearly to keep up to date on issues affecting the ITU. [32].

In charting a path to dedicated spectrum for space solar power, proponents must engage with several of the 19 study groups hosted by the ITU. [33]. The study groups are divided into three sections: Radiocommunications, Standardization, and Development. For space solar power the ITU-R (Radiocommunications) section is relevant as it is responsible for developing "the technical basis for decisions taken at the World Radiocommunication Conference, the body responsible for the Radio Regulations, the international treaty governing the use of radio-frequency spectrum and satellite orbits." These study groups provide a way for services looking to use RF spectrum to understand the technical implications of their project and to clarify the boundaries of the spectrum needed for the application. [33].

Commercial or public space solar projects will need to get the ITU study groups involved in analyzing the more promising schemes and get on the agenda of the World Radio Conference. There is tremendous competition between countries, companies, and militaries for access to spectral bands and SSP projects need to take into consideration these competing demands. A dedicated band for SSP and a clear technical understanding of the power limits and interference potential with existing systems should be a baseline for considering investment in SSP projects. Commercial projects should include a plan for spectrum allocation that is realistic given the decision-making time frame of the ITU. Early prototypes may utilize the spectrum bands that are dedicated to experimental and scientific exploration but should not base their transmitter and rectenna designs on having full access to that spectrum for the final system. The result could be wasted investment, suboptimal system designs, or project failure.

International cooperation will be important to allocation of spectrum for space solar power. The ITU functions on a consensus basis - no votes are taken. For publicly funded projects, working with allies and other interested parties to secure spectrum for an international SSP project could be the most expedient way to secure the needed spectrum through the ITU process.

2.International Cooperation

2.1. Space solar power projects world-wide

In many ways the U.S. interest in and development of space based solar power lags behind what other countries have invested in SSP. This section discusses the SSP studies, investments, and engagements of other countries and offers insight into where the U.S. could engage with partners and allies to develop a joint project or to avoid duplication and interference with each other's plans.

Japan

Japan has been an early leader in space based solar power research, investing in both paper design studies and experiments since the 1980's. Early studies include the Microwave Ionosphere Nonlinear Interaction Experiment (MINIX) in 1983 to study the effects of high-power microwave frequencies on the Earth's ionosphere, and the SPS2000 in the 1990s supported by the Institute for Space and Astronautical studies (now JAXA ISAS). [34].

In 2009, Japan enacted the "Basic Plan on Space Policy" plan that included space based solar power as one of four research and development projects. This policy directed agencies to work together to develop the components and strategies needed to demonstrate space based solar power. The current plan is to conduct a space to ground power beaming experiment by 2025, similar to the Caltech experiment recently conducted but with higher precision and a focus on beam steering technology. [35].

In 2022, Japan Space Systems announced its intention to demonstrate space based solar power by 2025. The research organization's goals are to "contribute to environmental conservation, the securing of natural resources, the development of the space industry and the utilization of geospatial information." [34]. They have been working on studying the feasibility of space based solar power since the early 2000's under funding from Japan's Ministry of Economy, Trade, and Industry (METI). The initial study conducted from 2001 – 2002 included a roadmap proposing interim 100 kW, 10 MW, 250 MW and final 1 GW demonstration projects. A follow-on analysis in 2003 covered static and dynamic attitude stability, methods, and feasibility of in orbit construction and operational considerations. From 2004 – 2007 they proceeded with system definition, evaluation, and laboratory demonstration. [35].

Japan's energy challenges have influenced its decision to invest in space based solar power. Japan imports 89.8% of its energy and its energy mix is dominated by fossil fuels including 39% energy from oil and 27% on coal, with 29% coming from nuclear power, and 21% from natural gas. [36]. This dependence on fossil fuels proved to be a vulnerability when Russia invaded Ukraine in 2022. The U.S. and its allies agreed to a $60/barrel cap on crude purchased from Russia to starve the country of its proceeds from oil, but Japan negotiated for a price above the cap and stepped up its natural gas purchases from Russia's Sakhalin-2 refinery. An official from Japan's Ministry of Economy, Trade, and Industry said, "Tokyo wanted to ensure access to Sakhalin-2's main product, natural gas, which is liquefied and shipped to Japan." [37].

Japan's commitment under the Paris Agreement includes achieving 46% reduction in greenhouse gas emissions below 2013 levels by 2030 and net zero by 2050, though they have yet to release a roadmap of how they plan to achieve these goals. Renewable energy, nuclear and storage could provide up to 90% of Japan's power, according to a study by the Lawrence Berkeley National Laboratory. [38]. Nuclear has suffered a significant loss in public support since the Fukushima Daiichi power plant disaster in 2011, which makes achieving net zero exceptionally challenging.

China

China included space based solar power as a key priority in 2008. Wang Xiji, a Chinese aerospace engineer and the first Chinese citizen inducted into the International Astronautical Federation Hall of Fame, was quoted as saying, "Whoever obtains the technology first could occupy the future energy market. So, it's of great strategic significance." [39]. In 2019, China declared its intention to develop a megawatt level space-based power system by 2035 according to China Academy of Space Technology (CAST). [40]. The initial investment began with $28.4 million U.S. dollars for development of component technology wireless power beaming in Bishan. [41]. CAST also announced its intention to perform wireless power transfer in low Earth orbit by 2028. [40] This would be the first phase of the program, followed by Phase 2 a test experiment in beaming power from geostationary orbit, and Phases 3 and 4 which would be full scale demonstrations of 10 MW and 2 GW in 2035 and 2050 respectively. [40]. Additional investigations include those by researchers at Xidian University who built a 75 m tall test facility to run experiments with power conversion and beaming through the atmosphere. [42].

China has also reached out in the past to develop international cooperation in space solar power. In 2012, China expressed interest in a joint proposal with India for a space-based solar power system. The following year in 2013, the Chinese government approved a proposal to begin development of its own space solar power station, followed by a feasibility study in 2014 by 130 Chinese experts from various agencies including the Ministry of Industry and Information Technology, the National Development and Reform Commission, and the Ministry of Science and Technology. [42]. In 2022, China made another leap forward in its space solar power project when it made apparent breakthroughs in key technologies related to the ground verification system of the program codenamed Zhuri or Chasing the Sun. [42].

China's interest in SSP appears to be tied to their climate goals, but their investment in SSP also advances their ambitions for space dominance. [43]. Funding for SSP advances technology in solar cells, in which China already leads, as well as microwave and laser power transmission, advanced power electronics, large scale space structure and space launch capabilities. Their proposed SSP roadmap includes megawatt level demonstrations by 2035 and a 1GW scale commercial system by 2050. [43].

United Kingdom

The United Kingdom has been unambiguous about its goals for a space solar power industry. In September 2021 it commissioned a study by the Frazer-Nash consultancy to evaluate the engineering feasibility of leading SBSP concepts and foundational technology for 10 GW of space solar power, as well as a cost and economic benefit analysis for future SSP in the UK. [44]. The study found significant benefits including in jobs and clean energy for the UK and advances the UK's Net Zero by 2050 commitment. They found a less than 12-month carbon payback period, affordable energy costs for residential and industry uses, and highlighted export opportunities for energy as well as the benefits of beaming clean energy to remote locations. [45]. The study also developed a technology roadmap for achieving demonstrations in the 2030's and a gigawatt scale system by the 2040's. [45].

Subsequently, at London Tech Week in 2023 the UK government announced £4.3 million in funding for UK universities and technology companies to advance innovation around SSP. [46]. The "Space Based Solar Power Innovation Competition" is part of the UK government's "Net Zero Innovation Portfolio. Awardees included Cambridge University for the development of lightweight solar panels, Queen Mary University for the wireless power beaming components. Additional grantees include: MicroLink Devices UK, University of Bristol, Satellite Applications Catapult Ltd, Imperial College London, and EDF Energy R&D UK Centre Ltd. [46].

The UK has also been in discussions with the Kingdom of Saudi Arabia for collaboration on a space solar power project. [47]. The meeting included the possibility of a collaboration between the UK company Space Solar Ltd and the new Saudi city NEOM being built to incorporate advanced technology. Investment from the UK and Saudi Arabia could attract significant private capital and provide NEOM with clean energy around the clock as well as jobs, intellectual property, and industrial contracts for the UK. [47], [48].

European Union

Motivated by Europe's Net Zero by 2050 goals, the EU has begun investigating space solar power to manage the inherent variability of traditional renewable energy resources like wind and terrestrial solar power. [48]. The desire for a diversified portfolio of energy sources was given new urgency with Russia's invasion of Ukraine and much of Europe's dependence on Russian natural gas. The volatility in energy prices placed a significant financial burden on European households and European governments learned that cheap natural gas came with high geopolitical costs.

The European Space Agency approved the SOLARIS program at the ministerial level in 2022. SOLARIS represents a preparatory program to establish the viability of a space solar power project before a final decision on investment is made in 2025. [49]. ESA is targeting SSP for terrestrial clean energy applications, though they point to relevant spin-off technologies and adjacent use cases such as in-space assembly and manufacturing, in orbit servicing and maintenance, efficiency in space transportation, and cross benefits to space exploration priorities. They also cite terrestrial spin-off dividends such as advanced robotics and power electronics from the development of SSP. [50].

Thus far, ESA has completed several studies of technical approaches, as well as economic viability in partnership with European industry, including Thales, Arthur D. Little, ENEL, and ENGIE. [48], [51]. In response to the recent NASA study, ESA was optimistic: "The conclusion of the report aligns well with similar studies in the UK, Japan, China and by ESA, that all show that there is a path towards SBSP becoming one of the cheapest and cleanest renewable energy sources that is scalable for our future energy needs." [52].

3.Commercial/Public-Private Partnership

3.1. Public-private partnership

The National Space Society (NSS) supports a public/private approach to developing and implementing space solar power. The Space Solar Power Demo development that the NSS describes consists of "minimal NASA oversight, milestone-driven fixed-price pay-outs, minimal exit criteria, substantial commercial partner funding commitments, non-traditional contracts (e.g., Space Act Agreements with NASA), commercial partner choice of energy market and energy consumer, enabling system development (e.g., space robotics), and at least two winners." [53]. The favored example of what this public/private partnership could look like is the successful COTS program in which NASA funded SpaceX and Orbital Science Corporation to develop a method to deliver crew and cargo to the International Space Station (ISS). The program was a mutually beneficial success for NASA, SpaceX, and Orbital Sciences, and exemplified the results of cooperation and collaboration of the private and the public sector in the space industry. NASA encouraged the U.S private space industry to develop reliable, cost-effective access to LEO and proved there is a "market environment in which commercial space transportation services are also available to government and private sector customers." [54].

Case Study: COTS

NASA was the lead investor in the Commercial Orbital Transportation System (COTS) project, a partnership to develop space transportation access to Low-Earth Orbit safely, reliably, and efficiently that lasted from 2006 to 2013. Specifically, this project sought to transport crew and cargo from private companies to the International Space Station [54]. Additionally, in NASA's words, "From its inception, one of the objectives of COTS was to "create a market environment in which commercial space transportation services are available to government and private sector customers." [55], [56]. It is considered a successful model of public and private collaboration in the space industry, especially with a budget of $800 million. This program was intended to bolster private and public cooperation as well as offer alternative solutions to relying on foreign cargo transfer vehicles. Once the program began in 2006, about 20 organizations submitted COTS proposals including Space X, Boeing, Lockheed Martin, and Orbital Sciences. In 2006, SpaceX and Rocketplane Kistler (RpK) were awarded the contracts, but NASA terminated the RpK deal due to insufficient funding. [57]. In 2008, Orbital Sciences and SpaceX were awarded the contracts, and by 2013, the rockets had been designed, constructed, and successfully launched in partnership with NASA.

Case Study: COMSAT

COMSAT is a global telecommunications company created through the Communications Satellite Act of 1962. [56]. The intention of COMSAT was for the U.S. Congress to create a private, federally funded corporation to develop international and commercial satellite communication. [56]. Its endeavors with commercial satellite communication allows for the corporation to work within the public and private sectors, balancing federal, commercial, and private projects. Many experts believe space solar power's future should follow the same trajectory as COMSAT and COTS, programs that can [58] work with many key players by utilizing government funding to incentivize private companies into developing the technologies.

3.2. Environment, Social, and Governance (ESG)

While the National Space Society claims that space-based solar power would have "essentially zero terrestrial environmental impact", many criticize this sentiment. This is specifically in reference to orbital debris, an already pressing issue when it comes to the thousands of satellite launches that occur every year. With the private sector's increase in space, many expect the number to skyrocket. Space is already becoming crowded, and debris is very costly to address compared to terrestrial pollution. Regulating the number of launches that will inevitably lead to orbital debris, as well as existing debris in space, is a vital element of maintaining that the environmental impact is fairly minimal when it comes to space solar power. NASA estimates the life cycle of hydrocarbon-based fuel and replacement of infrastructure is about 10 years, along with the baseline hardware lifetime [59].

3.3. Technology Transfer & Intellectual Property

NASA addresses march-in rights, which address the right of the government to require that a contractor grant a reasonable “nonexclusive, partially exclusive, or exclusive license” to a responsible applicant under specific circumstances.

Bayh-Dole Patent and Trademark Act

The Bayh-Dole Act Patent and Trademark Act of 1980 outlines that innovations federally funded by research should have the ability to become commercialized inventions that in some way benefits the American people. It also states if the patent owner denies granting the license, the government can grant the license itself. [60]. It is understood that inventions utilized in the LEO (low earth orbit) might be replicated and practiced by the government itself, or the government may delegate another entity to practice on its behalf. There have been no cases in which the Bayh-Dole Act’s march-in rights have been exercised by a federal agency, but the act states that the government does always retain this right.

3.4. R&D incentives, off-take obligations

The “Space-based Solar Power as a Catalyst for Space Development” Space Policy paper brings up the importance of a paradox: “…for there to be a reason to develop space, there must already be people and industry there.” [61]. The article makes the argument that space-based solar power is perhaps the best solution to this paradox due to its ultimate longevity and long list of potentials, including the potential to self-fund and accomplish green energy goals. This inherently suggests that advances in the space sector generally will ultimately benefit the possibility of space-based solar power.

On January 11, 2024, NASA released a report regarding space-based solar power, addressing many concerns that could affect the timeline of space-based solar power’s general use. The “most notable concern” was the safety of power beaming, although additionally mentioned were the concerns of cybersecurity as well as SBSP creating more orbital debris when many countries are trying to minimize their orbital debris footprint. [5]. On top of this, NASA addresses “regulatory challenges” that would make the process of SBSP more difficult, including spectrum allocation, orbital slots, launch approval, and the impact of these regulations on feasibility. [5].

4. Liability

4.1. Insurance

In 1978 Kosmos 954, a Soviet nuclear-powered satellite, crashed into Northern Canada causing radioactive debris to scatter across the northwest region. Out of the 12 large pieces of debris recovered, 10 were highly radioactive, prompting the conversation of who should be responsible for the disposal of the pieces [62]. As an ally, the United States ultimately aided Canada in the detection and disposal of the pieces, but many insisted it should be the Soviet Union’s responsibility to pay for and properly dispose of the debris their spacecraft deployed. While it was highly unlikely the Soviet Union would ever adhere to the request, this initially sparked conversation of liability of spacecrafts.

On March 8, 2024, a cylindrical metal chunk that crashed through the roof of a home in Naples, Florida. It was brought to the Kennedy Space Center for analysis where on April 15, 2024, it was determined that it was part of a cargo palette jettisoned from the International Space Station 2021 [63]. This invariably resulted in a conversation about which entity should be held responsible for the maintenance of an event like this. Many speculate it should be NASA as the agency is one of five international collaborators of the ISS and represents the United States. Many believe the agency responsible for the launch of the spacecraft from which the debris originates is responsible for any maintenance involved on Earth. Others argue it is up to individual countries’ governments to take accountability. In the last 50 years there has been some progress in deciding what entities should take responsibility for the liabilities of space technologies, with the University of Chicago Law School arguing as stated by the Liability Convention of 1962 in Article 7 of the Outer Space Convention, “...when harm on Earth is caused by an object in space or formerly in space, the state that launched the object is presumed to be liable—even if it had no hand in bringing the harm about.” [62].

Any space solar power system will involve hundreds or thousands of launches and constitute a very large orbital structure. It will likely be many times larger than the International Space Station and could cause damage to nearby satellites in the event of a failure. The development of a SSP project should consider the impact of failures, the history of past failures, and engage with liability for any potential failures in advance of launch. This could improve public perception, as well as hedge against future challenges before they arise.

5. Orbital Debris

5.1. Space Environment

There is no industry that is not touched in some way by the space domain. From the most obvious examples like communications and navigation to sectors like banking that have a less direct connection, the US relies on critical infrastructure in space to function properly. According to NASA's most recent estimates, there are "more than 25,000 objects larger than 10 cm are known to exist. The estimated population of particles between 1 and 10 cm in diameter is approximately 500,000. The number of particles larger than 1 mm exceeds 100 million." [64]. NASA's estimated total for the amount of material orbiting Earth is more than 9,000 metric tons.

Because an estimated 85% of orbital debris exists in LEO, it has been the focus of warnings about the dangers of debris creation and collisions. However, as the interest in GEO has grown due to the benefits of having a satellite that orbits in a fixed position with the Earth, GEO has gradually become more congested. Previous works have gone as far to say that orbital debris in GEO poses such a low risk that it may not even be necessary to move satellites in GEO to graveyard orbits at the end of their operational lifespan. [65].

In 2017, Analytical Graphics Inc. performed a study seeking to determine the threat orbital debris poses in GEO, and the results challenge this view. They concluded that while debris creating collisions are less common in GEO than in LEO, the chances of collision are growing, with a debris creating event likely to occur every 4 years in GEO. [65]. Further, a survey by ESA has reported that a higher number of fragmentation events have occurred in GEO. [66].

According to the researchers on the AGI study, "Although there is plenty of GEO satellite redundancy to weather a single mission-terminating collision with a debris fragment, of far greater consequence are GEO collisions with larger debris objects; all in the industry need to ensure that effective mitigation measures are implemented to avoid placing the entire market for GEO-based satellite services at risk." [65]. This is concerning for SSP because the large size and decreased maneuverability of a system capable of providing baseload power makes it more prone to debris collisions than an average GEO communications satellite.

Another important factor to consider is the potential for an SSP system to be targeted by an adversarial nation. Because of the benefits it would provide to both civilian and military sectors, it could be an attractive target for enemies seeking to cripple US capabilities. Direct ascent anti-satellite (ASAT) weapons capabilities of other nations have evolved to be capable of delivering a weapon into GEO. Additionally, the US is aware of the damage nuclear weapons delivered to space can have because of the Starfish Prime high-altitude nuclear weapons test, one of five nuclear tests the US performed in outer space. As space becomes increasingly militarized, and discussion of space assets as valid military objectives grows, so too should the conversation around the potential for intentional or unintentional collisions with an SSP system, and the effects it could have on the space environment.

5.2. Current Legal Regime

Outer space is governed by a legal regime primarily consisting of 5 agreements: The Outer Space Treaty, The Rescue and Return Agreement, The Liability Convention, The Registration Convention, and The Moon Treaty, as well as a handful of United Nations General Assembly resolutions. While these documents met the needs of spacefaring nations at the time of their conception, they contain little to no environmental protection for the resources of outer space. In fact, the legal regime established by these agreements has likely played a contributing role in the further creation of orbital debris.

Articles I and II of the Outer Space Treaty have a particular impact on the use of the outer space environment. Article I, paragraph 2 of the Outer Space Treaty states that “Outer space, including the Moon and other celestial bodies, shall be free for exploration and use by all states without discrimination of any kind, on a basis of equality and in accordance with international law. Article 2 of the Outer Space Treaty states that “Outer Space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means.” [67]. Both articles I and II of the OST were designed to allow for exponential development of outer space without consideration for the environmental impacts this could have.

The Moon Treaty advocates for better protection of the space environment, containing language referring to the harmful contamination of outer space. Despite this, it suffers from an almost complete lack of acceptance by the global community, with only 7 countries having ratified it. Thus, what little benefit it could provide for debris mitigation efforts is completely negated. [68].

The Liability Convention has the potential to be the most effective regulator of the space environment. Article III states "In the event of damage being caused elsewhere than on the surface of the Earth to a space object of one launching State or to persons or property on board such a space object by a space object of another launching State, the latter shall be liable only if damage is due to its fault or the fault of persons for whom it is responsible." [69] However, due to the ambiguous language of the treaty it is unclear if its provisions could be extended to environmental protection. This is further compounded by the treaty's narrow definition of damage. [68].

Aside from the five main treaties, the rest of the outer space legal regime is made up of UNGA resolutions. Several of them will likely have implications for SSP. While these resolutions are non-binding, they could help form the basis of future actions aimed at protecting the space environment. The UNGA Resolution on the Use of Nuclear Power Sources in Outer Space (UNGA Resolution 47/68) was created to address concerns of potential accidents involving nuclear powered space assets (UNGA 1992). The UNGA Resolution on the Recommendation on Enhancing the Practice of States and International Intergovernmental Organizations in Registering Space Objects (UNGA Resolution 62/101) sought to bring back the practice of registering space debris created by a country's space assets with the UN Registry. Before orbital debris was recognized as a growing problem by the global community, it was common practice to register debris, and in doing so acknowledge ownership and responsibility for damage it caused. [70]. Resolution 62/101 also approved the Inter-Agency Space Debris Coordination Committee (IADC) Space Debris Guidelines which are widely accepted as mandatory domestic regulations. [71].

While none of these treaties and resolutions adequately address the orbital debris problem, they represent a starting point for the critical work that must be done to ensure a safe and sustainable space environment, not just for future SSP systems, but all infrastructure operating in the space domain.

5.3. Orbital Debris Mitigation

A range of technical solutions have been discussed in previous sections for technologies that could be used for debris removal many of which could feasibly work. However, there is a glaring problem that must be addressed before active debris removal (ADR) can begin. Not only is the current legal regime not considerate of space sustainability, but it also safeguards ownership and property rights in a way that makes active debris removal difficult if not impossible. There are some potentially promising paths forward that could allow for ADR to begin.

One such approach advocates for the creation of an intergovernmental organization with the goal of remediating orbital debris. Such an organization could be tasked with overseeing the development of and operations of ADR technologies. Those who advocate for this approach to dealing with orbital debris argue it could accommodate the legal gaps halting progress on orbital debris in the current regime, share some of the costs, ignite new discussions, and bypass political deadlocks. [72].

A critical aspect to the success of such an organization will be the power to create and enforce binding international law. The non-binding nature of much of the current legal regime governing outer space has played a role in the stagnation of conversations and progress surrounding orbital debris. The creation of such an organization would require significant political will. This could be an opportunity for the US to step up as the leading spacefaring nation and set an example. NASA has noted that they plan to lead national and international efforts on orbital debris. This would do just that, as well as proving they are serious about the commitments they've made to ensure the long-term sustainability of the space domain. [72].

6. Health and Safety

6.1. Microwave safety concerns

On March 3, 2023, Caltech’s Space Solar Power Demonstrator, coined Microwave Array of Power-transfer Low-orbit Experiment, or MAPLE, became the first prototype to beam detectable power to Earth from space using a flexible, lightweight array of microwave transmitters and receivers. [73]. Previous demonstrations of similar technology include microwave transmitters sending power from Maui to Hawaii across 148 km in 2008 and Mitsubishi transmitting a 10-kilowatt beam over 500 meters in 2015. [74], [75]. In April of 2022, the Naval Research Laboratory successfully demonstrated radiofrequency (10 GHz) power beaming of 1.6kW over 1 km at the Army Research Field in Blossom Point Md. The Power Beaming and Space Solar Lead, Dr. Paul Jaffe said that “As engineers, we develop systems that will not exceed those safety limits [set by international standards bodies]. That means it’s safe for birds, animals, and people.” [76].

The same technology that would be used for space solar power has been used in demonstrations and is proven to offer no real harm to the environment and no greater threat to human health and safety than other existing satellites and space technologies that we already use. Energy density typically discussed for space-to-ground power beaming does not exceed 1000 W/m^2 which is comparable to the radiation from the sun on a cloudless day. [77].

6.2. Humanitarian Benefits

Electromagnetic beams do not have the same weather concerns as wires connecting power grids; even heavy rain would reportedly lose no more than 5% of its functionality. [73]. This would be an immense stride on the humanitarian front. During catastrophic natural disasters, times of conflict, and other humanitarian aid crises, the loss of electricity would make a massive difference in the access to and storage of food, water, medicine, healthcare technologies, and products, as well as the ability to share information during a time in which it is vital. Even during the 2020 COVID-19 pandemic, access to the internet was not only a way to stay connected, social, and entertained, but the only access to work and education for many. If a community loses power for an extended period due to a natural disaster, as so many did, for example after hurricane Maria hit Puerto Rico, there would be no access to financial resources, medical care, or communication, let alone education.

6.3. Cybersecurity

Cybersecurity threats are clearly a high risk for SBSP. Much like in power plants, space-based solar power stations would need to meet security requirements that cover infrastructure and cybersecurity issues. The implementation of a fail-safe method is essential to the continual use of SBSP as a cyberattack would pose as much, if not greater, vulnerability and threat than a physical attack. The “Space Solar Power and Cyber Security in Modern Spacecraft Operations” paper states, “space solar power has a vulnerability to a cyber-attack(s) since cyber security has not been a priority in government and private-sector space endeavors”. [78]. If SBSP is to be used on a scale that provides the most benefit, it would be constantly gathering usable energy and powering a large percentage of the world. SBSP would be the leading source of, not just renewable energy, but energy. A form of energy that is this powerful and universally beneficial would warrant priority when enabling proper security methods worldwide.

7. Public Engagement

7.1 Pushback against green energy

Primary among concerns about any novel technology are potential health and safety issues. A trend has arisen in which communities push back against solar farms with a litany of grievances. These include false claims about safety and toxins, as well as complaints about aesthetics and land use. Solar panels are unsightly and take up land that should be used for other purposes. [79], [80]. Solar panels kill birds. [81]. Solar panels cause catastrophic fires. [82]. Solar panels supposedly leak chemicals in the rain, contaminating the soil and groundwater with toxins they do not even contain, such as arsenic, germanium, hexavalent chromium, and perfluoroalkyl substances [81]. Solar panels have the ability to generate tornadoes because they reflect heat. [83]. These pseudoscientific hypotheses contribute to the overall platform of the fossil fuel industry, that alternative forms of energy should be abandoned.

Misinformation campaigns directed against solar farms are making inroads in communities in the United States, Canada, Australia, New Zealand, and across Europe. A nascent movement organizes itself with at least forty-five Facebook groups like Stop Solar Farms [84], online petitions on sites such as change.org [85], and activist groups such as Citizens for Responsible Solar [86]. This ostensibly grassroots movement has accomplished its aims in county after county, not only blocking new industrial solar farms but also enacting legislation to restrict future green energy projects [87]. A subset of NIMBYism (Not In My Back Yard), organized solar farm opposition is a force with the potential to be mobilized against other forms of alternative energy.

As with solar farms, communities have also targeted wind farms with false claims. Legislation opposing alternative energy projects often blocks both solar and wind farms by design. The playbook covers the same range of complaints about safety, toxins, aesthetics, and land use, while specific claims about wind farms differ. Wind turbines supposedly emit infra-sound [81], causing “wind turbine syndrome,” with negative health effects including vertigo, nausea, tinnitus, fatigue, sleep deprivation, migraines, miscarriages, and even death [88], [89]. The electromagnetic fields (EMF) around wind turbines supposedly drive additional health problems, including skin rashes [88], between them, over 200 symptoms have been cataloged. These nebulous claims bolster community antipathy to wind projects, which may also focus on disapproval of their noise and appearance.

The same technology may be treated differently by legal structures in different jurisdictions. Courts have not been unsympathetic to claims of personal injury due to supposed deleterious effects of wind turbines. A Belgian couple won 110,000 euros in damages from a French suit based on claims of turbine syndrome supposedly caused by the wind turbines 700 meters from their home. The local French power companies, having been fined, have also reportedly adjusted the turning speed of turbines in response to the suit [90]. It is possible that the presence of space solar power may drive similar tortious actions, and that resolution and setting of precedent may take years to work through the courts. While any technology may be treated differently in different jurisdictions, it is also true that issues will be regarded through a legal rather than a scientific lens, and that individual claims of nuisances will not need laboratory validation to prevail.

Like every previous innovation in energy delivery, space solar power will face critique and a certain amount of opposition. Aside from considerations of up-front cost and technical readiness, a common concern is that power beaming, either from lasers or from microwaves, may easily be used as a weapon. Other than the intrinsic fire hazard, lasers may also spark apprehension about eye injury. Concerns about the potential health effects of RF from SSP on humans, livestock, wildlife, and the natural environment have been addressed at least as early as the 1974 NASA report. The public will seek answers on these topics, as well as a range of queries that will be difficult to anticipate due to their non-scientific origins. Proponents of space solar power may anticipate such pushback and prepare a science education program designed for a lay audience.

An aspect of science education that should be included is the concept of the ‘trade space,’ in which one option or another will be chosen, whether actively or by default. It is not possible to avoid all forms of energy production out of an inability to commit to the least objectionable externalities. Rejecting space solar power, or wind turbines, or any other alternative energy source is a vote for the status quo. End users should be reminded of the negative aspects of whichever default energy delivery system they are using, whether it derives from fracking or coal or some other nineteenth- or twentieth-century form.

Considerations of the energy trade space will include nuclear power, not only because it is one of many possibilities for meeting the increased energy demands of the twenty-first century, but also because proponents of nuclear power are organized and vigorous in its defense.

7.2 Role of science communication

The role of science communication in educating the public about space solar power must not be underestimated. Every major technological innovation has gone through a phase of early adoption in which few users understood the basic science behind it. Thus, a phase of inaccurate assumptions and predictions would propagate, only to gradually fade as wider adoption disproved them. Potential objections may arise from two classes of critic: those with a strong science background, and the lay public. Science education should be calibrated accordingly.

Educated critiques of SSP tend to cover two areas: the effects of microwave radiation, and the possibility of its use as a space weapon. In both cases, the response would be that the power beaming transmitter is built to use only a limited range of frequencies. The health effects of radiofrequency are the same as walking through a metal detector, a technology that is both familiar and thoroughly tested through everyday human use. Similarly, those who hear “space-based solar power” tend to think of laser technology rather than RF, leading to the “space weapon” conjecture, and will readily understand that these are different technologies.

Simpler critiques of SSP may be so wide-ranging that a comprehensive forecast would still miss entire categories. Yet conspiracy theories tend to fall into genres, including health effects, government conspiracies, and aliens. Market research could test strategies to counter pseudoscience-based claims about “space lasers'' or potential carcinogenic effects. Ultimately, the best counter to paranoia is for accurate information to be conveyed by a trusted source, so the key to informing the general public would be to begin at the level of community leaders such as school teachers.

7.3 Pathway to acceptability

The pathway to public acceptance of space solar power will be different depending on regional needs. Some constituencies may view it as a national security issue, a means of achieving energy independence and avoiding reliance on geopolitical adversaries. Others may have limited options for green energy alternatives due to their geographic location; they may find space solar power one of the few available means to fulfill their increasing energy needs as their existing power sources reach capacity. Other countries may view space solar power as a strategic economic move that will both create jobs and serve as a profit center, allowing them to meet their own energy needs and sell power to their neighbors.

The United States, unlike Japan and the United Kingdom, has abundant natural resources and a large landmass with plenty of space for solar and wind farms. The rationale for space solar power will need to overcome polarized political associations as well as challenges from commercial interests. The most straightforward way to attempt this is to seek senatorial support by planning projects in areas in need of the jobs created by SSP, such as North Carolina, Georgia, and Nevada. These would include not just space-related jobs but also jobs manufacturing photovoltaics, rectennas, power electronics, batteries, and more.

Safety and effectiveness of space solar power will gradually be demonstrated through incremental technological development. Space-to-space applications are unlikely to incur a sense of threat among the general population. The 2023 Caltech MAPLE demonstration included power beaming from space to Earth without legal opposition. As incrementally more powerful transmitters beam toward ground-based rectennas, lack of harm or property damage should reassure the public about any perceived risks of the technology. Another way to dispel concerns of other nations is to aim the power beaming only within proprietary national borders - at least until these other nations begin to express wishes to partake of this new energy source.

8. A vision without a voice

A key challenge in the U.S. for developing a space based solar program is that the requirements, domains, and benefits from SSP overlap with several executive branch agencies and fit cleanly in none of them. Both NASA and the Department of Energy have been discussed as possible champions of the technology but neither agency has included SBSP in their roadmaps or budget requests. The Department of Defense has shown interest and funded several paper studies as well as demonstration projects. This section will detail the missions of various agencies that could be relevant to SSP and discusses current synergies and conflicts between the operational needs of a SSP project and the agency's current goals. We will also discuss the history of Congressional action and the need for explicit congressional appropriations to drive U.S. leadership in SSP.

8.1. The National Aeronautics and Space Administration (NASA)

The National Aeronautics and Space Administration's mission is to "explore the unknown in air and space, innovate for the benefit of humanity, and inspire the world through discovery." With 20 centers and nearly 18,000 civilian employees NASA also hires many more contractors and funds extramural academic research and Universities, companies, and research centers throughout the U.S and the world. It is led by Administrator Bill Nelson, former U.S Senator from Florida who in 1986 trained and flew with the crew of the Space Shuttle Columbia. [91].

NASA is organized into five mission directorates including Aeronautics, Exploration Systems, Mission Support, Science, Space Operations and Space Technology. The Aeronautics directorate conducts research and development relevant to the commercial aeronautics and aviation sector. The Exploration Systems Development Mission Directorate manages the human exploration system development for lunar orbital, lunar surface, and Mars exploration." [92]. The Mission Support Directorate manages support services from legal and contracting to facilities and infrastructure. The Science Mission Directorate directs and oversees scientific research and discovery in five key areas: Earth Science, Planetary Science, Biological and Physical Sciences, Heliophysics, and Astrophysics. The Space Operations Mission Directorate is responsible for enabling sustained human explorations operations in our solar systems. The Space Technology Mission Directorate advances technologies and capabilities for exploration of the Moon, Mars, and space. [92].

A space solar power project that is developed with the purpose of beaming solar energy down to the earth for terrestrial energy applications does not fit cleanly into NASA's mission of exploration and discovery. NASA's investments must fit within the budgets appropriated by Congress to fund the agency. In 2024, while the Biden administration's budget request for NASA was $27.2 billion, the spending bills that were passed into law shortchanged the request by $2 bn, holding spending near the 2023 budget of $25.4 bn. [93]. While the overall funding level remained the same between 2023 and 2024, Congress detailed hundreds of millions in cuts to certain programs and increases for others. Expected cuts to appropriations for the Mars Sample Return Program has already led to layoffs of Jet Propulsion Laboratory staff and contractors supporting the program. [93].

Without a clear connection between SSP and the NASA mission, and without appropriated funds from Congress it is unlikely that NASA will undertake significant investment in SSP capabilities. Doing so would require shifting massive resources from other projects not explicitly determined by Congress. It is not only politically risky; it could damage other priorities and morale in the agency when other valued efforts are cut to provide resources for SSP. NASA has also invested significantly in nuclear power for deep space exploration and lunar base energy generation. The energy density of nuclear and radioisotope energy sources, as well as their long lifetime is likely attractive.

8.2. The Department of Energy

The mission of the Department of Energy is to “ensure America’s security and prosperity by addressing its energy, environmental, and nuclear challenges through transformative science and technology solutions.” [94]. The DOE runs the 17 national laboratories, funding innovative research in energy efficiency, generation, and storage, and manages the U.S nuclear capability, including nonproliferation and environmental efforts. [94].

In the 1970’s during the energy crisis, the Department of Energy was early to collaborate with NASA on a study of space solar power, based on Dr. Peter Glaser’s description of the concept in 1968 in the journal Science. The high cost of launch was cited in early studies that questioned the feasibility of SSP at the time. Since the 1980’s and the end of the oil crisis the DOE has not had meaningful involvement in SSP concepts. Though it does participate in the Interagency Advanced Power Group (discussed below).

While plummeting launch costs have changed the calculus of space solar, the DOE has had limited involvement in the more recent studies. It maintains an information page on SSP on its website but has not funded any major explorations of the concept since the initial study with NASA in the 1970’s. [95]. In some ways this highlights a key challenge for SSP projects. The largest and grandest use-case for SSP is in terrestrial power delivery to back up variable renewable energy sources. DOE has funded and investigated many competing technologies, but its domain does not extend to space. The bright dividing line, where NASA invests in the space domain, and DOE invests in the terrestrial domain, leaves little room for beaming power between the two domains.

Where DOE has partnered with NASA and provided space capabilities it has focused significantly on nuclear technology. NASA and DOE signed an MOU on Radioisotope power systems for NSAS deep space exploration. [96]. Given DOE's historic founding out of the Atomic Energy Commission and the development of nuclear energy for civilian purposes, it is understandable that for clean firm energy generation, the DOE leans heavily on investment in nuclear technology. [97].

8.3. The Department of Defense

The Department of Defense has the longest history in the U.S. of investigating and investing in space solar power projects. Air Force Research Laboratory and the Naval Research Laboratory have been the most prolific investors in SSP. Paper studies by students at the Army War College, as well as NRL and AFRL have explored the national security use cases and technical feasibility as well as proposing potential designs. [98].

The Space Vehicles Directorate at the AFRL in collaboration with NRL and Northrop Grumman funded the Space Solar Power Incremental Demonstrations and Research Project (SSPIDR) in 2018. [99]. The goal of the program is to mature and advance technology areas needed for SSP, "to provide uninterrupted, assured, and logistically agile power to expeditionary forces." [100]. AFRL identified six key technology areas that require investment for a successful SSP project, including, "Deployable Structures, Energy Generation, Thermal Management, Distributed Control, RF Beaming, and Metrology (beam forming)." [100].

The SSPIDR program is investing in three demonstrations that advance these technology areas. The "Space Power InfraRed Regulation and Analysis of Lifetime (SPIRRAL)" experiment will explore the challenges posed by thermal management in the extremes of the space environment, the Arachne project will demonstrate a "sandwich tile" that converts solar energy to electricity to radio frequency and finally beam it to earth. The Space Power INcremental DepLoyable Experiment (SPINDLE) project is aimed at maturing deployable structures in space. [100].

8.4. Interagency Activity

The Interagency Advanced Power Group is “federal membership organization dedicated to the facilitation of information exchange in areas of advanced power technology.” [101]. It provides information exchange and coordination between federal agencies on science and technology priorities and strategies. Membership includes the Department of Energy, Department of Transportation, Air Force, Army, Navy, and NASA. Its four working groups include Chemical, Electrical Systems, Mechanical Systems, and Renewable Energy Conversion Systems. Within the Renewable Energy Conversion Systems working group the IAPG has a panel on Space Power that “encompasses spacecraft renewable electrical power technologies, including technology gaps, emerging advanced component technologies, testing of new technologies…as well as integration of these technologies into advanced space power systems. Component technologies include but are not limited to, renewable energy sources (e.g., photovoltaics), advanced solar panel and blanket technologies, and advanced solar array technologies.” [101]. The Current Co-Chairs of the Space Panel include Robert Walters (Air-Force), Margaret Stephens (Navy), and Jeremiah McNatt (NASA). [101].

8.5. Congressional Action

Given the limitations on the executive branch agencies, a policy roadmap for space solar power must acknowledge the critical role that Congress plays in setting the agenda for the agencies and for appropriating funding. Without Congressional action, it is unlikely that NASA, DOE, or the DOD will be able to initiate a substantial SSP effort. It would require them to take funding away from other priorities that fit squarely within their missions, and much of the funding they receive is already mandated directly from Congress.

Congress has shown no interest in space solar power since the 1970’s, however in June 2023, Representative Kevin Mullin (D-Calif) introduced an amendment to H.R. 2988 to include space solar power to a section of the bill that provides statutory authority for collaboration between NASA and DOE on cross-cutting research. The amendment was passed out of committee and passed the House in December 2023. [102]. Representative Mullin was quoted as saying, “Although the technology to gather solar energy in space and send it to the surface as electricity is not yet commercially viable at scale, we already know from early research that it is possible.” [103].

9. Beyond Energy

Many proponents of space solar power have emphasized the final goal of a gigawatt scale system for firm dispatchable solar energy. Earlier we have discussed some intermediate milestones and niche markets for energy that could support early-stage efforts in space solar power. Energy generation is not the only benefit that this technology offers. The development of space solar power is likely to generate spill-over effects, impacting the maturation of important technology in other sectors. This section details the possible spin-off dividends of developing SSP systems.

ISAM:

In-space Servicing, Assembly, and Manufacturing (ISAM) is described in the 2022 ISAM National Space Strategy as "a suite of capabilities, which are used on-orbit, on the surface of celestial bodies, and in transit between these regimes." The name ISAM breaks these capabilities into three general categories, servicing which refers to the post-launch modification and alteration of space technologies in their pre-launch state, assembly referring to the action of physically attaching objects in space, the aggregation and connection of components in space, and the construction of systems in space, and manufacturing referring to the fabrication of materials and components in space. [104]. ISAM includes a wide range of capabilities including refueling, debris removal, orbit transfer, and transformation of raw or recycled materials. [104].

A successful space solar power project will both utilize and advance ISAM capabilities. In-space assembly will be a critical piece of the successful deployment of a large-scale space solar array. In the likely case that a modular design will be pursued to reduce the cost and ease of launch, the ability to assemble many pieces into a large array will be critical. In-space servicing will also be essential to maintaining and repairing solar power satellites and their associated in-space infrastructure. This will allow for a longer lifespan as a modular array can have pieces gradually replaced over a longer period of time as opposed to fully replacing the array with a shorter lifespan. Down the line in-space manufacturing capabilities may come into play in the form of manufacturing components such as solar cells and structural materials on-orbit needed to maintain and repair a space solar power system.

The pursuit of a space solar power system will drive the advancement of ISAM capabilities. Including likely advancements in robotics with increasingly autonomous and dexterous abilities to perform more complex tasks, assembly techniques and capabilities to improve the quality, efficiency, and speed in in-space construction, and assembly and construction capabilities for increasingly complex and sophisticated structures. In-space manufacturing, being the most adolescent of the three categories, will likely see many advancements including the ability to process and refine materials optimized by the space environment such as medications whose production requires the use of a vacuum chamber. Advancements in in-space manufacturing will also improve the efficiency and reliability of manufacturing processes in a microgravity environment.

ISRU:

In Situ Resource Utilization is a concept that refers to the extraction, refinement, and utilization of space resources from celestial bodies for a number of potential purposes. While the concept itself has been discussed since the Apollo program, advancements in ISRU only date back to the 1990's and early 2000's. ISRU capabilities are still in their infancy, however, advancements in lunar water and oxygen extraction have been made within the last few years. [105]. Currently, missions like NASA's Artemis program are actively exploring ISRU technologies for extracting wat [106]er and other resources from the Moon and Mars. [107]. Water extraction is one of the most prominent examples of ISRU research and advancement currently. The International Mars Ice Mapper Mission is a joint effort between NASA, JAXA, ASI, and CSA, that sought to map out deposits of ice on Mars for future extraction and utilization. [106]. ASA is doing similar research on the Moon with their Lunar Icecube Mission as well as pursuing lunar regolith utilization. [107]. Regolith, the layer of loose, heterogeneous material covering solid rock, can be used as a source of raw materials for building structures and producing oxygen. Various methods for processing regolith are being developed and tested, such as heating for oxygen extraction and 3D printing for construction.

ISRU capabilities may play a role in the successful development of a space solar power array and will also benefit from advancements made in the process. Developing SSP systems requires advanced technologies for space-based power generation, transmission, and storage. These technologies could have synergies with ISRU, leading to advancements in areas such as robotics, automation, and resource extraction techniques. Utilizing in situ resources could also decrease the potential environmental impact of pursuing an SSP system by decreasing the number of launches transporting materials from

Earth for construction and maintenance. One of the biggest potential future advancements in ISRU capabilities with the prospect of making ISRU commercially significant is the extraction and production of fuels and propellants such as liquid oxygen and liquid hydrogen. This would reduce the reliance on Earth, and the number of Earth to space launches needed for large scale projects such as an SSP array. It will also come with the benefit of scalability, allowing for a range of projects from small scale robotic missions to crewed Mars missions.

Advanced Robotics and Automation:

Robotic technologies are advancing at a rapid pace, becoming more sophisticated with an ever-growing range of uses. Along with these advancements, industrial automation is spreading to a multitude of sectors including transportation, healthcare, and manufacturing. Robots are being equipped with more advanced manipulation capabilities allowing them to perform intricate tasks with precision. This will be particularly important for tasks involving the assembly of complex structures in space.

Further advancements in robotics and automation made in pursuit of a SSP system will result in spin-off dividends that will not only benefit the space sector, but also many terrestrial industries. The manufacturing industry is the most likely beneficiary of these advancements. Beyond general improvements in efficiency, cost, and precision, SSP will also build a better understanding of the needs involved with the manufacturing of large complex objects, opening the door for automation of projects like high-rise or bridge construction. Advanced automation could also remove the need for people in sectors like mining and quarrying that are dangerous and potentially expose workers to hazardous materials. It could also positively impact people in countries such as the Democratic Republic of Congo, where human rights abuses such as forced, and child labor take place in cobalt mines. [108].

Orbital Debris Mitigation

Maneuverability is a critical capability of space objects. An ever-increasing amount of orbital debris is present in space resulting from events like the Iridium-Cosmos satellite collision in 2005, and the recent 2021 Russian destructive ASAT test, both of which produced pieces of orbital debris numbering in the thousands. Because a kilometer scale space solar power array will lack the maneuverability of smaller space objects like satellites, and even the ISS, its successful implementation will likely drive orbital debris mitigation technologies. Not only would active debris removal (ADR) missions benefit from advances in space transportation and propulsion, but the debris removal technologies also themselves would benefit from innovations in other areas of a space solar power system. In particular, likely advancements in robotics and ISAM could further advance current concepts for debris mitigation and lay the groundwork for innovative new debris removal technologies.

Advanced Cooling and Thermal Management

Thermal control is crucial for maintaining the temperatures of space systems throughout their operational lifespan. If temperatures exceed certain levels, equipment can be damaged or experience a significant drop in performance. Repairing damage to sensitive electronics and optical components in space is not possible, which is why space thermal management systems must be highly efficient and reliable to ensure optimal function. [109].

Due to the immense thermal management requirements of a large scale SSP system, its pursuit will drive innovation in thermal management technologies. The sheer size of an SSP system capable of producing baseload power would introduce challenges that are not present with current space systems. The complexity of such a large system, likely having many components and subsystems that require precise temperature control, would require sophisticated thermal management systems. Because such a system is likely to be placed in GEO, it will have to contend with harsher conditions than the majority of satellites which reside in LEO. [110]. Additionally, SSP systems are designed to collect solar energy, meaning they need to be able to withstand constant exposure to intense sunlight.

SSP’s Moment in the Sun

Space solar power has reached a point in its development where it is actively being pursued by multiple nations and commercial companies. Initial power beaming was successfully demonstrated in 2023, and a space solar project is slated to be launched in 2025. [111]. Whether research and development of SSP will continue is not in question; the question is whether the United States will participate or stand by as an observer.

The first issue with SSP adoption is choice of architecture, which includes both design and means of transmission. The three options under consideration are optical laser, RF, and orbital mirrors. While power beaming by optical laser eliminates the time delay of spectrum allocation by the ITU, the trade-off is atmospheric attenuation. Technologically, RF power beaming appears to be most effective, but it does introduce the issue of spectrum allocation. Orbital mirrors may interfere with astronomical observation. [112]. Regardless of which method of power transmission is chosen, a design must ultimately be selected out of several currently proposed.

The second issue is spectrum allocation. Spectrum is a highly valuable, finite, and thus contested resource. SSP will always have to compete with other technologies that rely on the electromagnetic spectrum, including telecommunications, radar, WIFI, GPS, and the continuing possibility of novel technologies. The ITU meets only once every four years; as preparation is unlikely to happen by the June 2024 meeting, [112]. a delegate to the 2028 ITU meeting could request to add allocation for SSP to the 2032 agenda. An advantage of this time window is that it allows eight years to coordinate agency sponsorship and complete design selection.

The third issue with the sponsoring of a SSP project by the United States is which agency will take the lead in the three-way standoff between NASA, the Department of Energy, and the Department of Defense. This impasse could potentially be broken by Congress with an order to develop SSP.

Space solar power has the potential to be the pivotal technological leap of the twenty-first century. It could provide jobs, serve as a profit center, help achieve Net Zero carbon emissions, spin off valuable technological innovations, and provide abundant power to meet increasing energy needs as well as assist developing countries in attaining equity in their standard of living. Space solar power is technologically feasible and is already developed to the point where it may return investments threefold. Those nations that are moving forward with SSP today will be first to experience the coming paradigm shift.

Acronyms

ADR	Active debris removal
AFRL	Air Force Research Laboratory
ASAT	Anti-satellite weapon
ASI	Italian Space Agency (Agenzia Spaziale Italiana)
CASSIOPeiA	Constant Aperture, Solid-State, Integrated, Orbital Phased Array
CAST	China Academy of Space Technology
COMSAT	Communications Satellite Corporation
CONFERS	Consortium for Execution of Rendezvous and Servicing Operations
COTS	Commercial-off-the-shelf
CSA	Canadian Space Agency
DOD	Department of Defense
DOE	Department of Energy
EMF	Electromagnetic fields
ESA	European Space Agency
ESG	Environmental, social, and governance
FCC	Federal Communications Commission
GEO	Geostationary orbit
GHz	Gigahertz
IAPG	Interagency Advanced Power Group
IEEE	Institute of Electrical and Electronics Engineers
ISAM	In-Space Servicing, Assembly, and Manufacturing
ISRU	In situ resource utilization
ISS	International Space Station
ITU	International Telecommunication Union
JAXA	Japan Aerospace Exploration Agency
LCOE	Levelized Cost of Energy
LEO	Low Earth Orbit
MAPLE	Microwave Array for Power-transfer Low-orbit Experiment
METI	Ministry of Economy, Trade and Industry
NASA	National Aeronautics and Space Administration
NRL	Naval Research Laboratory
NSS	National Space Society
NTIA	National Telecommunications and Information Administration
OSAM	On-Orbit-Servicing, Assembly, and Manufacturing
PV	Photovoltaics
RAND	Research and Development Corporation

RF	Radiofrequency
RpK	Rocketplane Kistler
SBSP	Space-based solar power
SSP	Space solar power
SSPIDR	Space Solar Power Incremental Demonstrations and Research Project
SPINDLE	Space Power INcremental DepLoyable Experiment
WRC	World Radio Conference

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