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Opportunities and Challenges for Space Solar for Remote Installations

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14. ABSTRACT
This study report extends previous efforts exploring the concept of providing power to military and remote installations via solar power satellites. The goal of the study was to determine the feasibility of a coordinated development effort for this capability. Included are key findings of opportunities and challenges, as well as recommendations for advancing the development of technologies applicable to space solar for remote installations. The study team determined that there remain significant unresolved technological, economic, legal/political, operational/organizational, and schedule challenges inherent in the development of the capability. Important questions regarding the most promising approaches and prospective utility for operationally relevant contexts have yet to be definitively answered because of technological immaturity and uncertainties in non-technical areas. Because of the potential game-changing nature of space solar, investments in several critical areas are recommended, the foremost of which is power beaming technology.

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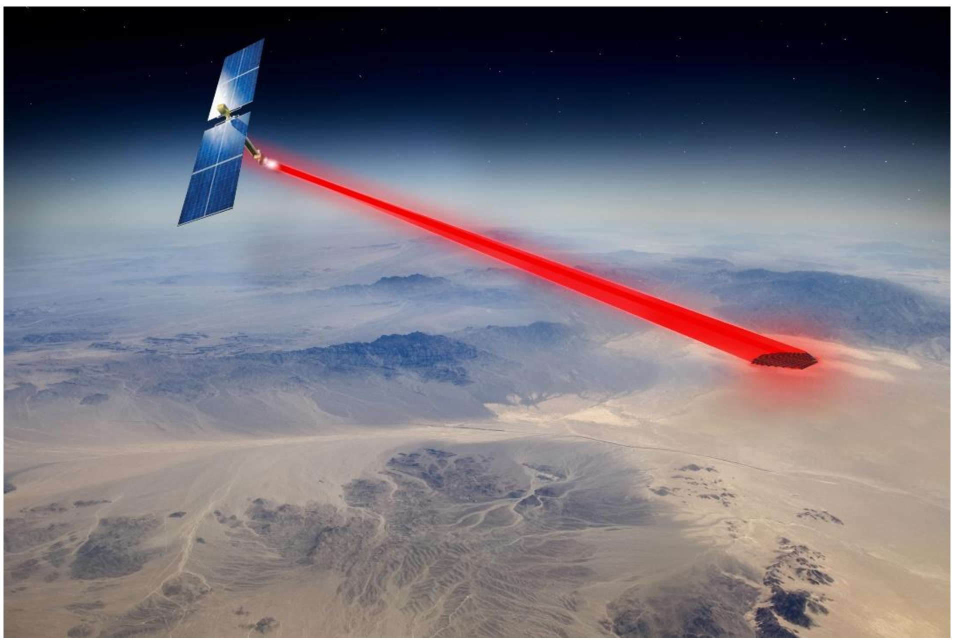
OPPORTUNITIES AND CHALLENGES FOR SPACE SOLAR FOR REMOTE INSTALLATIONS



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1 EXECUTIVE SUMMARY

Energy is critical for essentially every human activity. A practical capability to send energy to a range of sites directly from space to augment or supplant traditional military energy supply lines presents compelling benefits. As the Department of Defense's energy requirements evolve, pursuit of existing and prospective energy options has yet to illuminate a path toward a long-term, resilient, and logistically tenable solution.

Power beaming technology forms the foundation of a possible solution. Space solar would depend intrinsically on this technology. With space solar, unfiltered, continuous sunlight is collected and converted by satellites in space and sent to points of need on Earth. This approach unlocks novel operating scenarios and capabilities for military and space operations. Key advances in spacecraft mass-production, power conversion, lightweight materials, commercial reusable launch, and space robotics within recent years have led subject matter experts to suggest that renewed in-depth investigation of these possibilities is warranted.

This study report extends previous efforts in order to clarify the timeframe of potential feasibility and identify prospective means of providing power to military and remote installations via space solar. The goal of the study was to determine the feasibility of a coordinated development effort for a military and remote installation energy resupply capability via space solar. This report includes key findings of opportunities and challenges, as well as recommendations for advancing the development of technologies applicable to space solar for remote installations.

The study team determined that there remain significant unresolved technological, economic, legal/political, operational/organizational, and schedule challenges inherent in the development of a deployable space solar capability. Important questions regarding the most promising approaches and prospective utility for operationally relevant contexts have yet to be definitively answered because of technological immaturity and uncertainties in non-technical areas. In light of these challenges and questions, paired with the potential game-changing nature of space solar, **now is the time for the Department of Defense to lead measured investment by Operational Energy stakeholders in these six key areas: (1) Space Solar Collection, (2) Power Beaming Transmission, (3) Power Beaming Reception, (4) Receiver Power Distribution, (5) Architecture Analytics, and (6) Supporting Technologies.** Technology gaps identified during the course of the study appear in Appendix A, and the development plans formulated are captured in Appendix B.

Efforts in these six areas will directly support the execution of integrated demonstrations of progressively increasing capability, which in turn will give insight into applicability to emerging paradigms, such as battlefield electrification and the shift towards autonomous systems. The likely economic viability of space solar for military energy supply as compared to alternatives should be reassessed regularly by tracking progress and trends of these four metrics: space transportation cost, space hardware cost, specific power of the space segment, and the contribution of costs from the receiver segment. In parallel, the legal/political roadblocks should be addressed, particularly for spectrum and orbit allocations. Likewise, it is critical to monitor and at minimum maintain parity with foreign developments. Operational utility should be further discerned and informed via modeling and analysis efforts. Together, these will shed light on the schedule horizon and appropriate further steps forward.

2 BACKGROUND

Sunlight in space, at the Earth's distance from the sun, is brighter and uninterrupted compared to sunlight on Earth, except in the Earth's shadow. Because of this, considerable effort has been devoted to creating a way to utilize this effectively boundless source of energy for practical use on Earth. Since power is a key prerequisite for effectively all military and civilian activities, space solar has potential means to exploit this huge source of energy [1] with profound geopolitical implications. International peers and competitors are investing in technologies related to space solar development, evidenced in part by large-scale power beaming demonstrations performed in Japan [2] [3] and interest in China [4] India [5] Russia [6] and elsewhere [7].

Benefits of a solar power satellite (SPS) system might include unlimited, clean, constant, nearly globally transmissible energy to support military operations by providing increased flexibility and resilience, and with potentially decreased risks and costs. The logistics of energy resupply might be simplified via power beaming directly into theater from space, versus the transport of liquid fuels. This concept would dovetail with other efforts to migrate to battlefield electrification [8] [9] [10] [11] and the shift towards autonomous systems [11] [12]. Novel operating scenarios and capabilities could be unlocked.

Previous investigations of space solar for military applications were reviewed in the undertaking of this effort [13] [14] [15] [16]. Since their completion, pivotal advances in spacecraft mass-production, power conversion, lightweight materials, commercial reusable launch, and space robotics have unfolded, motivating a re-examination of this concept.

This study combined lines of inquiry that had previously been considered mostly in isolation to formulate:

(1) an assessment of space solar specifically for remote installations,

(2) systems suitable for power levels significantly lower than the utility grid,

(3) detailed identification of technology gaps and opportunities,

(4) an evaluation of space solar in the context of current and future alternatives, and

(5) a consideration of future requirements and paradigms in view of increasing electrification and automation of military assets.

This report can serve as a tool of immediate use to decision makers, and is extensible to future studies by design.

2.1 Energy for Defense

Forward bases remain the primary way of supporting today's global conflicts, despite efforts to transition to more expeditionary approaches [17]. U.S. armed forces use these installations frequently as a means of establishing strategic positions without the full expenditure required by a permanent base. At any given moment, hundreds of such facilities are in use around the globe, many in areas that are subject to resupply challenges [18]. When a conflict in a given region ends, or when the politics of a region change, such installations are typically moved, transitioned to host nations, or abandoned. Numerous previous studies have addressed vulnerabilities, opportunities, and considerations for energy as it pertains to such installations [19] [20] [21] [22].

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2.2 The Space Solar Concept

Millions of terawatts of sunlight pass through the region of space surrounding the Earth in which our satellites orbit daily. A small fraction of this power would be more than adequate to satisfy the energy required for military operations, provided it could be harnessed effectively and transported in a usable form.

In the late 1960s, American scientist and engineer Peter Glaser detailed a novel approach to global energy: the solar power satellite. The basic concept of the original SPS is straightforward: a large platform positioned in space continuously collects and converts solar energy into electricity [1]. This power is then used to drive a power beaming system that transmits the collected energy to receivers on Earth. Offering implementations that would be unaffected by nighttime, weather, and seasonal variation, space solar could enable global power distribution without a global grid infrastructure, thereby overcoming critical limitations of ground-based solar power systems. For forward operating bases (FOBs), space solar could reduce, or even eliminate, the need for considerable logistical burdens and dangers associated with transporting fuel to its destination.

This concept has been the subject of numerous systems studies and a smaller number of technology development efforts during the past five decades, documentation of which is available online [23]. These have included isolated, episodic efforts around the world, with relatively steady technology research and development activities in Japan. Though space solar requires no new physics, there has been debate as to whether it would make economic sense to pursue its development, with well-reasoned, lucid arguments presented on both sides [24] [25].

At its core, a solar power satellite system needs to accomplish two functions: (1) collection of energy and (2) delivery of that energy to the point of need. The ensemble that performs these functions can be divided into two major segments: (1) the space segment and (2) the Earth segment. The power beaming method, typically microwave or laser, has a substantial impact on the space segment size and power link implementation. The emplacement of the space segment would require suitable launch and in-space transportation means. Figure 2-1 illustrates one approach that uses concentrating mirrors, photovoltaic cells (PV), and microwave power beaming [26].

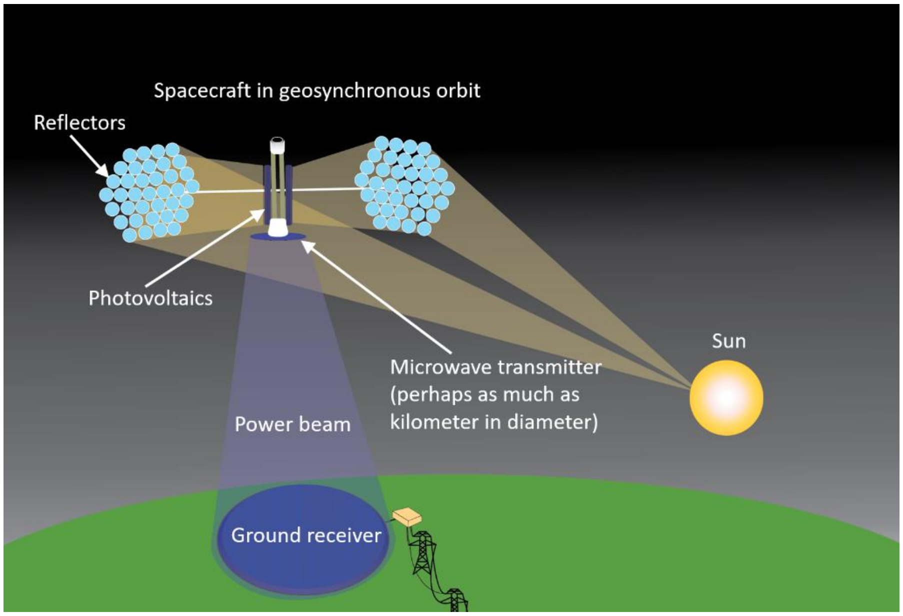

Figure 2-1 - One of many proposed space solar concepts; depiction is not to scale. Adapted from [26]

3 THE EVOLUTION OF DOD ENERGY USES AND NEEDS

3.1 Motivation for Considering Energy Alternatives

Multiple military realities come into consideration when looking to alternatives, like space solar, as a possible energy option as outlined below.

(1) *The need to reduce logistics burdens and minimize energy resupply risks.* Significant effort and resources are needed to ensure that forward bases and remote installations have sufficient, dependable, and resilient energy sources. The concomitant logistics tail to provide this capability is laden with overhead costs and risks. As finite fossil energy resources become scarcer or more problematic to utilize, alternatives become necessary. The ability to send continuous and mission enabling energy to remote installations without exposing warfighters and support personnel to direct engagements, roadside bombs, and other hazards would be of significant importance to national security, and could provide tactical and long-term strategic advantages. Practical space solar has the potential to open up a range of associated national security implications [27].

(2) *The ongoing transition away from fossil fuels.* Since the DOD and its branches recognize that systems using fossils fuels should be viewed as a bridge to more sustainable alternatives [28], there has been a focused investment in longer-term research and shorter-term opportunities to effect the transition. Sending energy wirelessly from space to installations that would otherwise receive energy derived from fossil fuels would directly support this transition. The capability would complement existing efforts, such as an increased focus on electric and hybrid vehicles for military operations [9], and also address the current paradigm in which batteries play an increasingly crucial but onerous resupply role.

(3) *The need to increase energy architecture flexibility*. The nature of satellite services allows for provision of utilities to areas devoid of extant infrastructure. For example, satellite-based communications have been utilized for decades with increasing levels of sophistication. Whether the need is in the middle of vast expanses of ocean, remote deserts, or difficult-to-access jungles, satellites provide essential and reliable communications for military forces. Space solar might do the same for power: provide a global resource that can be used essentially at will. If a base is relocated or closed, the energy provided to it could quickly be redirected or reallocated.

(4) *The transition to autonomous systems.* Looking toward a future where our military operations may often depend more on autonomous and remotely operated assets than on "boots on the ground," the ability to provide wireless energy resupply becomes even more valuable. Although a traditional forward base has needs besides energy, including water, food, and ammunition, a prospective future installation or group of autonomous systems might not have such needs. Consider an installation or mobile group populated principally by drones that require electricity for mobility and that use electrically-powered directed energy weaponry, or a decentralized system of autonomous vehicles. Power beaming via space solar or another suitable source could then present a near-total means of resupply.

(5) *The expanded use of energy harvesting.* Another possibility for wirelessly transmitted energy from space solar is for energy harvesting augmentation. As interest in energy harvesting for sensors and other applications has increased, a fundamental limitation has been the total amount of energy available in a given operational environment. Space solar could help remove this limitation and uncertainty by providing known, constant energy for sensors and other operations. Currently the economics for this scenario appear daunting, and so other alternatives are being explored.

3.2 Characteristics of Potential Service Regions

Several characteristics of locations should be considered for their suitability for energy resupply via space solar or other means. These include latitude, local geography, typical weather patterns, and the natural environment. Different locations must also contend with the possibility of local hostilities and political factors. Proposed energy resupply means must often take into account the realities under which installations must operate, including perceptions of safety by host governments and populace, while adhering to established force protection guidelines [29] [30].

To allow various space solar architectures and their likely power beaming links to be evaluated and compared with each other and with existing and prospective alternatives, representative design reference regions (DRRs) were developed, covering a range of the characteristics outlined above. Seven DRRs spread globally across the geographical combatant commands were considered, with some deliberately located inland where sea-based resupply would be difficult. They were:

(1) *Low-latitude Pacific island*, between 20°N and 20°S (South China Sea, Indonesia-New Guinea, Micronesia, Melanesia, and Polynesia)

(2) *Mid-latitude island*, above 20°N and below 20°S (Hawaiian Islands, all of Mediterranean, Formosa, parts of the Caribbean, and Indian Ocean islands)

(3) *Mountainous desert*, between the equator and latitude 35°N (mountains of Afghanistan, Pakistan, Iran, and eastern Turkey)

(4) *Subtropical desert*, between latitudes 10°N and 35°N (northern Africa, Ethiopia, Somalia, and several Persian Gulf states)

(5) *Tropical jungle*, between the equator and 15°N latitude (Indochina, Sub-Saharan Africa, Central America, and northern South America)

(6) *Polar*, above latitude 60°N (Arctic sea lanes, including land- and sea-based sites)

(7) *Distressed urban*, (Aleppo, Syria)

3.3 Characteristics of Potential Receiving Sites

The location and other characteristics of a given installation may be largely independent. It might be geographically large or small, densely or sparsely populated, and long- or short-term, and its mission could vary widely. These factors will affect the type and magnitude of energy consumption: if most of an installation's consumption for the foreseeable future is in the form of liquid hydrocarbon fuel for ground vehicles and aircraft, the benefit of a large and robust supply of electricity has limited utility. Conversely, if energy consumption is principally in the form of electricity for base support or mission activities, a source like space solar may be more attractive. The contrast between the different types of consumption can be seen in Figure 3-1, in which the category *Base Support Activities* principally represents electricity consumption and the category *Air and Ground Operations* represents fuel consumption for mobility. Data is from June 2008.

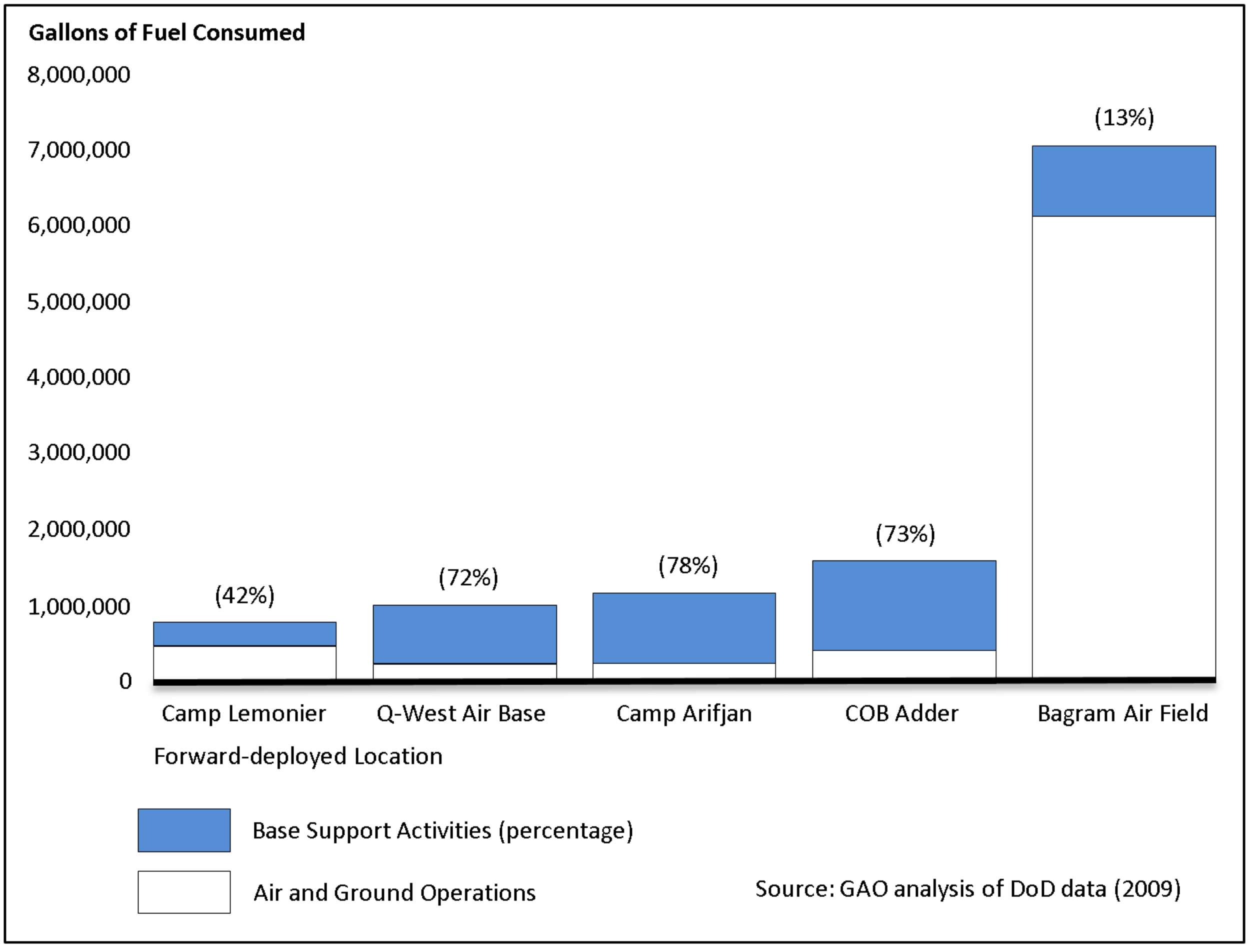

Figure 3-1 - Energy use types for selected installations for June 2008. *Abbreviations*: COB: Contingency Operating Base; GAO: U.S. Government Accountability Office; Q-West Air Base: Qayyarah Airfield West (Mosul District, northern Iraq) [31].

Bulky energy sources, or those that present significant logistical overhead, may not be justified for a small facility with few personnel and little equipment. Reduction or simplification of sources could be welcome for larger facilities that require ongoing and massive energy resupply. These considerations are mapped onto the spectrum of base sizes in Figure 3-2, which also shows the generalized relationship between base size, cost of energy, and per capita usage.

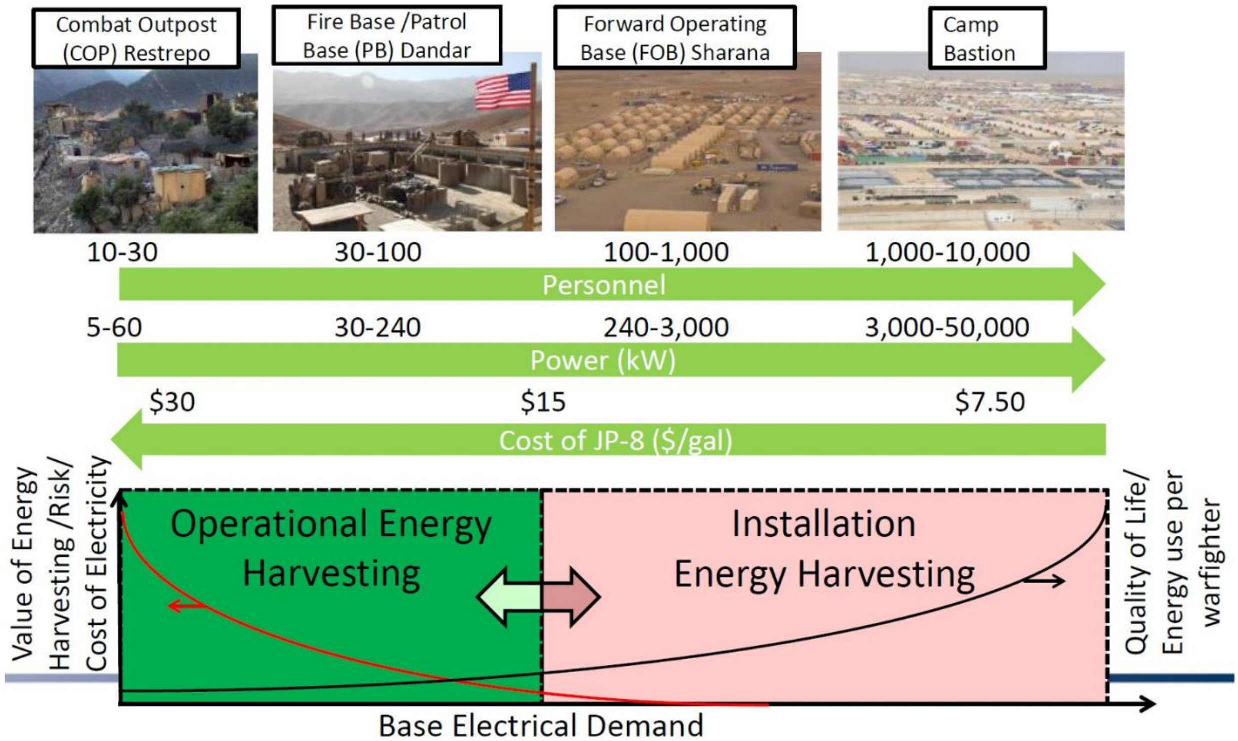

Figure 3-2 – Generalized energy cost and consumption for different installation sizes [32].

For the purposes of this study, the term *installation* is used to include the superset of traditional FOBs, newer expeditionary force-oriented encampments, and prospective future energy receiving locations. The breakdowns of four classes of bases used in the Strategic Environmental Research and Development Program Sustainable Forward Operating Bases report were considered for this study [20], with the recognition that power required per person is likely to be higher moving into the future. These classes are summarized in Appendix G.

3.4 Farther Term DOD Basing Architectures

The ability to provide significant electrical power to a remote location, with fuel delivery requirements substantially reduced or eliminated, could drive future basing architectures, particularly if it occurred in concert with a trend toward more capable electric vehicles and electric weapons, such as those using directed energy. Alternately, as synthetic fuel production technology matures, it might be possible to generate fuels in situ using electricity and appropriate feedstocks [33].

The availability of beamed power from space could enable previously unrealizable novel basing architectures and military tactics. With abundant electrical power, the role of the FOB might evolve into a crewless or minimally-staffed facility, possibly even airborne or mobile, merely for supporting autonomous or remotely operated systems, sensors, and communications. Airborne installations could implement a high-altitude receiver for incoming beamed power, which would reduce or eliminate atmospheric effects. Receiving power at altitude would fully open up the trade space for the selection of shorter wavelengths for power beaming. The shift towards intelligent systems may enable installations capable of self-repair that would be essentially maintenance free, or revolutionary and unprecedented force structures and presentations that might radically reshape the character of warfare, once the challenge of energy provision has been addressed.

4 SPACE SOLAR ARCHITECTURE

4.1 Overview

Although there are no fundamental scientific breakthroughs required to implement even large-scale space solar deployments, many of the underlying technologies needed to implement space solar are at a nascent stage. To better understand the challenges implicit in the deployment of a space solar system, a generic functional breakdown is depicted in Figure 4-1. Additional subsystem options and implementation details can be found in Appendix F and in [14] and [34]. The selection of a particular technology for a given segment may drive or constrain the options for other segments.

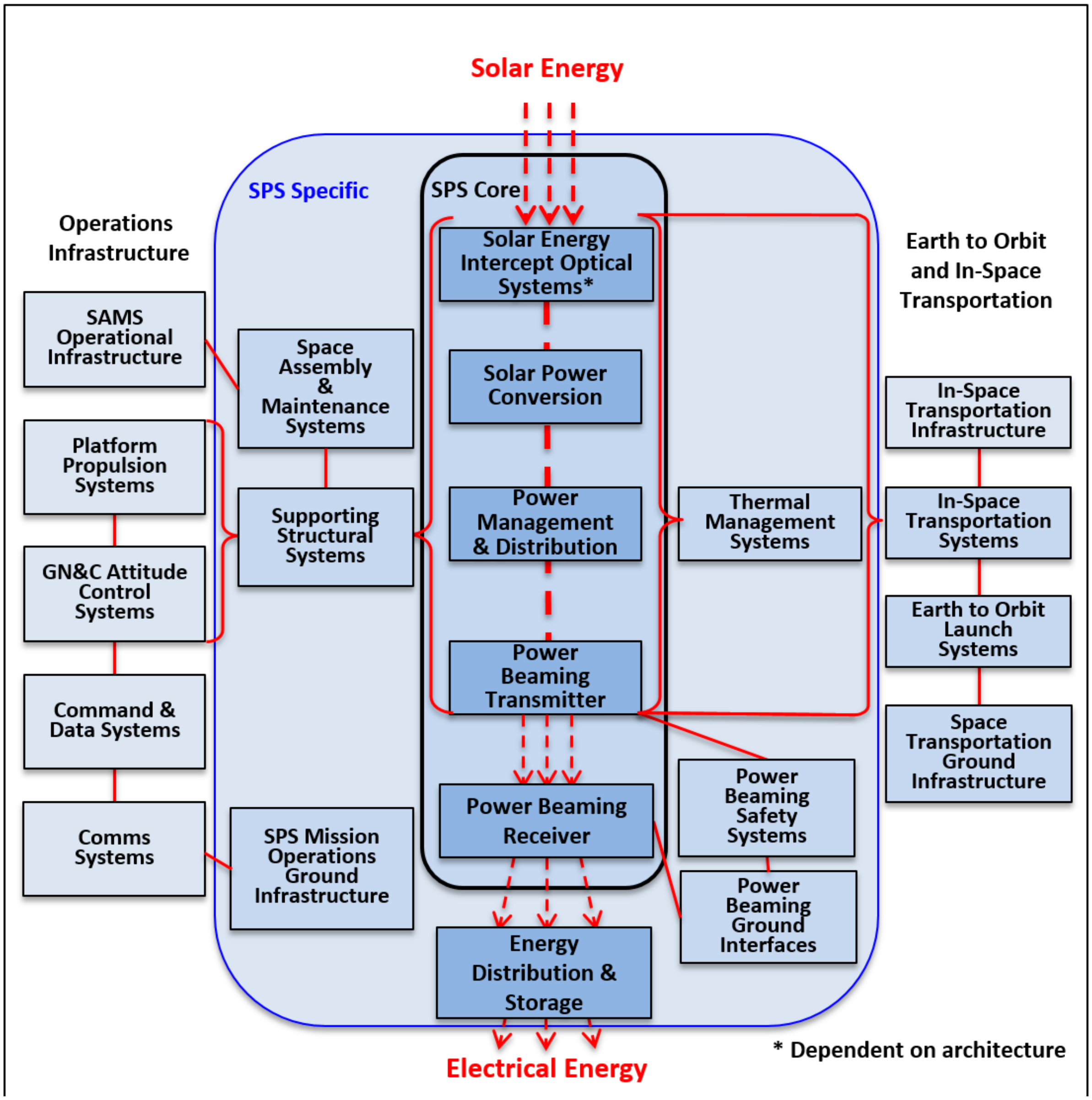

Figure 4-1 – Generic space solar architecture functional block diagram. *Abbreviations*: SPS = solar power satellite; SAMS = space assembly & maintenance systems; GN&C = guidance, navigation and control; Adapted from [34]

4.2 Technology Readiness Levels

Although the technology readiness levels (TRLs) of component technologies and needed systems vary widely depending on the architecture pursued, general assessments can be made. These are tabulated in Figure 4-2. ***It is absolutely critical to recognize:***

(1) ***Because the scale of proposed space solar implementations generally dwarfs prior systems, there is limited utility in extrapolating or rolling up subsystem TRLs to the system level.***

(2) ***Subsystems with higher TRLs may still pose major challenges because of cost or insufficient performance considerations.***

(3) ***Differing proposed architectures depend intrinsically on specific technologies with lower TRLs than shown.***

Examples of technologies for the third point include optically precise large-area thin-film reflectors (TRL 3), large high voltage power management for space (TRL 4), and thin-film high efficiency electronics for space (TRL 3).

System or Subsystem	TRL	Notes
Space Solar Power System	**5*/4***	**RF / Laser - **Note component TRLs below are not demonstrated at scale or cost point likely required for space solar***
Operations	**5**	**Lessons from decades of crewed spaceflight and satellite operations**
Space Assembly and Maintenance Systems	6	Capability demoed in LEO (ISS), GEO DARPA Program in development (RSGS)
Platform Propulsion Systems	9	Chemical and electrical systems on orbit, but not at required scale
GNC Attitude Control Systems	6	Not yet demonstrated at space solar scale
Supporting Structural Systems	5	Extremely high area to thickness ratios drive likely required
Command / Data Systems	9	Decades of heritage
Communications Systems	9	Extensive heritage on satellites
Mission Operations Ground Infrastructure	7	Scale needed to support space solar ops still conceptual
Solar Energy Interception and Conversion	**6**	**Conventional spacecraft heritage**
Solar Power Generation	9/6/4	PV / heat engine / solar-pumped laser; but none at required scale or cost
Power Management & Distribution	6	Must manage losses and waste heat, highly architecture dependent
Thermal Management Systems	**6**	**Lower masses likely needed for space solar, not demonstrated at scale**
Power Beaming Transmitters	**6/5**	**Subscale RF demos in lab, outside, space / laser demos in lab and outside**
Power Beaming Receivers	**6/5**	**Rectennas below 100 GHz / laser receiver PV**
Power Beaming Safety Systems	**5/4**	**Preliminary demos performed for RF / laser**
Retrodirection	5	Several Japanese-led demos
Other Safety Systems	5/4	Power density and power beaming modality will affect safety systems
Ground Interfaces, Including Storage	**6**	**Not yet prototyped for space solar, but likely similar to ground solar**
In-Space Transportation Systems	**6**	**Dependent on implementation, possible GEO stationkeeping precursors**
Earth-to-Orbit (ETO) Launch Systems	**8**	**Reusable Falcon 9 or Heavy, reflight frequency likely needed not demoed yet**

Figure 4-2 – Technology readiness levels (TRLs) of systems for space solar. Abbreviations: LEO = low Earth orbit; ISS = International Space Station; GEO = geosynchronous orbit; DARPA = Defense Advanced Research Projects Agency; PV = photovoltaic; RF = radiofrequency; RSGS = Robotic Servicing of Geosynchronous Satellites (a DARPA program) GNC = guidance, navigation and control.

5 PROSPECTIVE DOD SPACE SOLAR ARCHITECTURES

Most existing space solar architectures were conceived with the utility grid in mind as the output for the energy collected. In order to justify the massive anticipated expenses for system development, they tend to maximize the amount of power to be provided, typically on par with utility scale nuclear or hydroelectric plants: on the order of ≥1 gigawatt. At the time of writing, as there is no overseas military facility anywhere in the world that requires 1 gigawatt, the existing architectures are largely mismatched for remote installation supply, and even more so when limited receiver area and mobility requirements are imposed. For this study, notional power beaming links and constellation configurations were formulated for a range of probable remote installation requirements.

5.1 Key Architecture Parameters

Interrelated factors that most affect space solar architecture design include the following: (1) the total power to be delivered, (2) means of solar energy collection, (3) the wavelength at which power will be beamed from the satellite, (4) the orbit in which the satellite segment will operate, (5) the targeted launch mass, (6) the cost of the space system, and (7) considerations concerning the implementation of the power receiver. These factors are considered in the creation of bounding constraints for remote installation power provision via space solar.

5.2 Architecture Bounding Constraints

To frame the architecture assessment, top-level and necessarily somewhat arbitrary guidelines were formulated for the creation of an initial operational capability to be deployable within ten years:

- Power: Provide between 10 kW to 10 MW from the output of a deployed receiver.
    - Rationale: Generally, more power is better, but there is a limit to how much power any given location would require. The physics of power beaming and power densities, as driven by the system implementation, affect the amount of power provided to a given area. Accounting for the typical power demands and historically available installation areas, this is likely an appropriate range for a “building block” power element, much as current practices use generators of various sizes as “building blocks” to support installation power needs.
- Cost: Not to exceed $10 billion to an initial space demonstration capability.
    - Rationale: Although the actual amount of research and development needed and the corresponding costs are elusive, it was assessed that there would be a political threshold, beyond which embarking on the development would be untenable. $10B was selected based on a survey of the investment levels for other major national space programs [35]. It must be emphasized that the initial operational capability would almost certainly <u>not</u> be expected to be cost competitive with energy alternatives.
- Peak power density at the ground receiver: Generally, within accepted limits for the operating frequency or wavelength, approximately 100 W/m^2 for 2.45 GHz, 5.8 GHz, 35 GHz, and 94 GHz; and 1,000 W/m^2 for 1550 nm. These limits are per the Institute of Electrical and Electronics Engineers (IEEE) [36] and the American National Standards Institute International (ANSI) [37].
    - Rationale: Power density is a critical parameter because it intrinsically constrains the utility of the system. Because of the possibility of aviation operations in the vicinity, and the potential need for personnel to access the receiver area, existing safety limits are a place to start, despite the fact that these constraints will make it challenging to produce a source that is competitive on a power density basis (effective W/m^2 available to users) with existing alternatives. This does not preclude future situations where integrated safety systems, operational procedures, and interlocks could safely support higher power

densities. Existing thresholds are intended to have safety margins, but recent studies of radiofrequency (RF) safe power densities suggest that the long-term effects could pose concerns [38].

- Maximum receiver area: 0.8 km^2, nearly equivalent to a circular area about 1 km in diameter.
  - Rationale: A review of publically available map data for larger bases, such as those shown in Appendix D, suggests the total area within the protected perimeter rarely exceeds 20 km^2. A visual land use assessment further suggests for these larger bases that a 1 km diameter receiver may be an upper bound. Generally speaking, less area is available at smaller bases. It may be possible to implement power beaming receivers on top of existing buildings or structures, or as airborne platforms, necessitating smaller allocations for space at given installations.

Using the above with additional assumptions, a number of secondary constraints may be derived:

- Maximum space segment mass: 555 metric tons (t)
  - Rationale: Taking the $10B cost constraint and assuming: (1) that approximately 25% of the funding is applied to launch, (2) the cost of placing hardware in GEO is ~$4,500/kg (using a Falcon 9 or a Falcon Heavy in "standard payment plan" configuration with a notional 30% discount on current pricing and a notional ion/electric with 3500 seconds specific impulse transfer stage, details in Appendix I) the mass that can be deployed is approximately 555 t over about 37 Falcon 9 or 29 Falcon Heavy launches. As a point of comparison, the International Space Station's mass is approximately 420 t [39]. It is projected that innovations in space transportation could reduce launch costs significantly, but these have yet to fully materialize [40] [41]. For orbits lower than GEO, this cost would likely be reduced somewhat. It is also assumed that the space segment would employ only materials from Earth. Though the cost of space solar might be reduced by using extraterrestrial materials, substantive exploitation of such materials was deemed likely to fall beyond the 10-year period of consideration for this study. This in turn implies that the cost per unit mass of the space segment hardware cannot exceed $13,500/kg if the total space segment mass is 555 t, neglecting the cost contributions of other elements, like the ground segment.
- Maximum receiver mass: 1,600 metric tons
  - Rationale: Assuming the maximum receiver area of 0.8 km^2 from above, and an areal mass density of 2 kg/m^2, the maximum mass should not exceed 1,600 t. The areal mass density assumption is approximately ten times that of a common heavy-duty tarp [42], and one-tenth that of a deployed terrestrial photovoltaic and battery storage system [43]. As there are currently no representative examples of deployable power beaming receiver systems, this figure has great uncertainty. The effects of additional hardware that is likely to be needed, such as conversion/distribution electronics, support structure, transport casing, and energy storage may increase the areal density nearer to that of deployed terrestrial photovoltaic and battery storage systems. As a point of reference, 1,600 t kg is approximately equivalent to 21 fully-loaded C-17 cargo planes [44]. To deploy a Basic Expeditionary Airfield Resources (BEAR) force presentation package for 3,300 personnel requires about 74 C-17 loads using 463L pallets [45]. It is anticipated the volumetric density of the receiver hardware will result in a mass limitation before a volume limitation for air transport, so a maximum volume is not specified.

5.3 Power Beaming Link Scenarios

For adaptation of a space solar architecture to military or remote installation use, there must be at least one viable power beaming link scenario from the satellite(s) to the receiving site. Mission needs will drive the system design. This is shaped largely by the constraints on the receiver site(s), and by the flexibility in other variables to accommodate those constraints. For grid applications, several prospective power beaming links have been designed [46], but these are generally not applicable to remote installation cases because larger land areas are envisioned to be available for grid-connected space solar.

In addition to the amount of power transmitted, there are three types of factors that affect the performance and characteristics of a power beaming link in practice: (1) geometric factors such as the separation between the transmitter and receiver, the size of the transmit and receive apertures, their orientation and alignment, and the operating frequency; (2) implementation factors such as the use of concentration, the transmitter's areal power distribution, and the device efficiencies of the components in the transmitter and receiver; and (3) the losses arising from the effects of the atmosphere and weather, further described in Appendix N. A shortcoming in any of these areas may render a proposed link impractical. Table 5-1 shows prospective power beaming link scenarios using a Gaussian approximation for beam collection efficiency and the influences of the three categories of factors, guided by the constraints outlined above, with the resulting power available at the receiver. Note that the first three cases are at a 20,000 km orbital altitude, necessitating constellations for continuous coverage, and incurring additional requirements for beam control and tracking versus the fourth case.

Table 5-1 – Prospective Power Beaming Link Scenarios

Factors	Parameter	μwave MEO	mm-wave MEO	Optical MEO	Optical GEO
Geometric	Frequency (GHz)	5.8	35	194,000	194,000
	Wavelength (μm)	5.17E+04	8.57E+03	1.55	1.55
	Transmit aperture diameter (m)	500	350	2.5	2.5
	Link distance (km)	20,000	20,000	20,000	35,786
	Receive aperture diameter (m)	1,000	500	11	50
	Beam collection efficiency (%)	13.4%	47.4%	38.6%	95.7%
Implementation	Intercepted sunlight power (kW)	268,606	131,617	269	5,368
	Space segment conversion efficiency (%)	18.3%	7.4%	11.6%	11.6%
	Transmit power (kW)	49,042	9,734	31	620
	Receiver segment conversion efficiency (%)	73%	47%	62%	62%
Atmospheric Effects	Minumum clear sky losses at sea level (%)	1%	6%	5%	5%
	Cloud/weather losses at sea level (%)	minimal	varies	varies	varies
Receiver Peak Output Parameters	Power density at receiver center (W/m^2)	9	32	160	994
	Average power density across receiver (W/m^2)	8	22	107	257
	Receiver average output power density (W/m^2)	6	10	66	158
	Receiver output power (kW)	4,742	2,024	6	311

Input	Calculation

Notes about each case:

<u>Microwave MEO</u>: 5.8 GHz was determined to be the lowest frequency likely to be usable in a remote installation case, given the constraints. This arises from the low beam collection efficiency associated with fixed aperture sizes and longer wavelengths. Of particular interest is that it was necessary to set the orbital altitude lower than geosynchronous orbit in order to achieve even the comparatively low beam collection efficiency within the other constraints. Relaxing the receiver size constraint would allow the collection of additional energy. Departing from the use of a geosynchronous orbit implies that a constellation would be necessary to provide power on a constant basis. At a 20,000 km Medium Earth Orbit (MEO), single satellite in-view durations might be about four hours, and occur about twice per day, depending on the geographical

location and orbit particulars. 5.8 GHz offers the highest demonstrated device efficiencies and the best clear sky, foliage, and weather performance of the four cases, but would almost certainly require the largest and most massive space segment. With a 500 m “sandwich” implementation, in which a single structure would be used for sunlight collection and transmit aperture formation, nearly 270 MW of power is intercepted, and neither the IEEE limit for safe power density of 100 W/m^2 on the ground for an access-controlled area or the 10 W/m^2 IEEE limit for the general public is exceeded. Reflectors for directing and possibly concentrating sunlight on to the photovoltaic surface would likely be needed, and are currently at a low TRL, as previously noted.

Millimeter wave MEO: Increasing the frequency to 35 GHz improves the beam collection efficiency, but worsens conversion efficiency and clear sky losses. Keeping the 20,000 km orbit selection again means a constellation is needed for persistent coverage. The smaller 350 m aperture will not intercept as much sunlight as the Microwave MEO case, but has higher transmission directivity due to the shorter wavelength. Safe power densities on the ground for access-controlled areas are maintained.

Optical MEO: Using 1550 nm allows for dramatically smaller transmit and receive apertures to achieve higher beam collection efficiencies, and relaxes the safe power density limit by a factor of ten to 1000 W/m^2. However, 1550 nm will be much more susceptible to variability from weather and airborne particulate losses than either the microwave or millimeter wave cases, assuming power reception is accomplished within the troposphere. A sandwich approach is likely to be less suitable for laser transmission, so the sunlight collection and transmission apertures were assumed to be decoupled. The Optical MEO case was sized with consideration for smaller installations with less available receiver area and lower power needs. Like the previous two cases, the MEO orbit means a constellation would be needed for persistent coverage.

Optical GEO: Because of optical’s intrinsically low diffraction compared to longer wavelengths, an implementation employing geosynchronous orbit is more viable than it would be for microwave transmission, given the constraints. This case uses GEO, and increases the power collected and transmitted by more than an order of magnitude, but otherwise has the same benefits and drawbacks as the Optical MEO case. Unsurprisingly, some previous studies have concluded that laser transmission is the best fit for using space solar to provide energy to military bases [47] [48] or as a starting point for any solar power satellite system [49].

For different assumptions and operating concepts, a wide range of other approaches are possible. In previous studies of space solar for grid power, the power incident on the rectenna is usually on the order of 80% of the power emitted from the transmitter, contingent on the size of the rectenna [34]. This accounts for losses due to atmospheric attenuation and the economy of reducing the collection area to capture only the bulk of the transmitted energy. For tactical applications, the proportion of transmitted energy collected could be significantly lower if it satisfies mission needs and still compares favorably with alternatives. A minimum-sized viable “building block” unit capability could use parallel systems to increase available power, much as multiple generators can be added to bases today to increase the available power. The size of the unit capability would heavily depend on the operating wavelength selected, with shorter wavelengths being amenable to smaller unit sizes.

5.4 Power Beaming Safety

As mentioned in one of the Architecture Bounding Constraints, power density produced by a solar power satellite may pose safety concerns for people and objects exposed to the beam. For both laser power beaming and RF power beaming, there are safety standards for limiting continuous human exposure to specific power density thresholds, as seen in Table 5-2. Averaging times vary, see standards for details.

Table 5-2 - Selected Power Density Safety Limits

Safety Standard	W/m^2
IEEE Std C95.1™-2005 for 2 GHz to 100 GHz uncontrolled area	10
IEEE Std C95.1™-2005 for 3 GHz to 300 GHz controlled area	100
ANSI Z136.1-2014 limit for 1400nm to 1000µm	1,000

For laser wavelengths shorter than 1400 nm, the power density thresholds are lower because of the potential for retinal damage. In the microwave region, the International Commission on Non-Ionizing Radiation Protection puts the threshold in controlled areas at a value of 50 W/m^2, half the limit specified by the IEEE.

Safety architectures have appeared in the literature for power beaming, where the beam would suspend normal operations if a foreign object were to approach [50] [51]. Such architectures might include an uplink or sensors on the receiving antenna and in other areas to detect and send a signal to the satellite to defocus, divert, dim, or douse the beam as needed if an object were detected near the path, such as a person, aircraft, or spacecraft.

Despite the safety standards, the military in certain circumstances exceeds the safety limits by several orders of magnitude when the risk of harmful exposure has been effectively mitigated. In a region where an RF transmission exceeds the limits, such as for a radar, barriers and other measures are implemented for personnel safety [52]. A space solar system using microwaves might implement a similar perimeter if the power density standards were to be exceeded. For laser power beaming, safety eyewear specific to the wavelength could be worn to prevent harm to personnel by beam transmission at levels higher than the maximum permissible exposure. Conrad, Rowley, and Thampan, have explored laser safety challenges for power beaming systems [53]. In any case, the possibility that the hazard area could appear over a wide field of regard poses a profound challenge with safety and geopolitical implications.

For situations with autonomous systems and no personnel, power density limitations may be greatly relaxed or effectively unconstrained. This would open up a wholly separate trade space for power beaming link and system design.

5.5 Receiver Architecture

A receiver on the ground would receive and convert the beam transmitted by the solar power satellite into usable power. The architecture would depend on the power beaming method. Because power beaming is effectively line-of-sight, terrain masking affects where ground receivers can be deployed effectively. The amount of received power generally increases with larger receiving aperture areas or larger incident power densities. Increasing the power density beyond certain thresholds has potential power handling limitations, thermal management concerns, and safety drawbacks as described in the safety section.

A microwave receiver would include an antenna to capture the beam and rectifying functionality to convert the beam into usable power. For a tactical situation, the rectenna would most likely be similar to the "thin-film" architectures demonstrated by Brown [54]. This approach allows for low mass, enhanced portability, and rapid deployment. An example of the hardware from Brown's effort, paired with a present-day portable solar deployment system that might be representative of how it could be deployed is shown in Figure 5-1. Brown's receivers have demonstrated RF-to-DC efficiency as high as 91%. If the average power density of the receiving antenna were to be 100 W/m^2, at the IEEE safety limit for controlled areas from 3 GHz to 300 GHz, the receiving antenna could output about 1 MW if the diameter of the receiver were about 120 m, and might weigh about 250 kg. For comparison, this is approximately the same area as a FIFA-compliant soccer field (120 m x 90 m) [55].

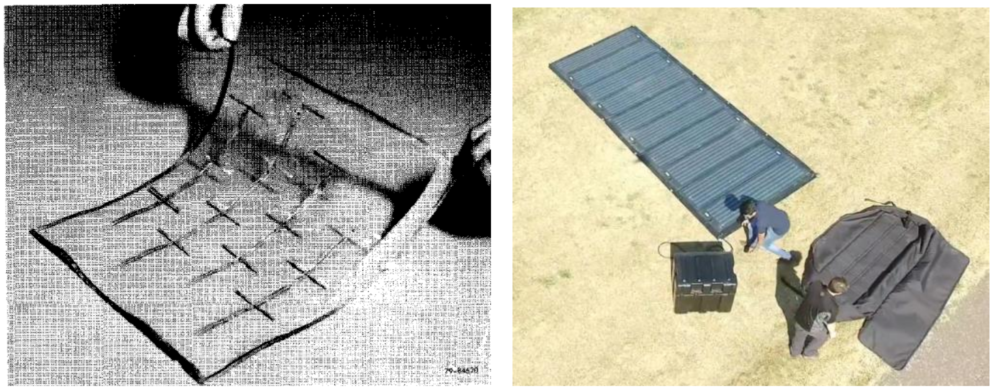

Figure 5-1 - (a) A thin-film rectenna created by W.C. Brown [54] and (b) deployment of Renovagen's Fast Fold solar array [56]

A laser receiver would be made of photovoltaics, similar to a photovoltaic array used for ground-based solar, but instead of sunlight it would convert a narrow-band optical frequency beam into usable power. The military has developed photovoltaic arrays for tactical use, such as the Solar Portable Alternative Communications Energy System (SPACES) or the Rucksack Enhanced Portable Power System (REPPS), which can be folded into a portable carrying case or the Ground Renewable Expeditionary Energy Network Systems (GREENS), which allows for portability with larger arrays, though they are not thin-film [57]. Laser power beaming might implement a similar photovoltaic architecture. At 1,000 W/m^2, the ANSI safety limit for 1550 nm, a 1 MW receiver with 50% efficient bandgap-tuned photovoltaics would require about a 50 m diameter area, just less than 20% of the area of a regulation FIFA soccer field. PV for sunlight is designed to convert a wide range of wavelengths, rather than being optimized for a single wavelength, and peak at about 45% for research cells [58]. Photovoltaics tuned to a particular wavelength have demonstrated conversion efficiencies as high as 70% at 840 nm at high light intensities [59].

The thin-film designs for the rectenna and laser photovoltaic arrays would allow for flexible deployment configurations. Receivers might be rolled and un-rolled, similar to a tarp covering a baseball infield, or to rapidly deployable HESCO barriers, which are effectively unfolded from the back of a truck in motion [60]. They might also be installed upon or integrated with buildings, tents, or other structures to be emplaced at a remote installation, potentially affording planarity and rigidity for wind protection. Approaches that have been demonstrated for fast deployment of terrestrial photovoltaics could be used as well, such as the Renovagen Rapid Roll T, which claims a 2-minute deployment time [43]. Possible deployment scheme analogs are shown in Figure 5-2.

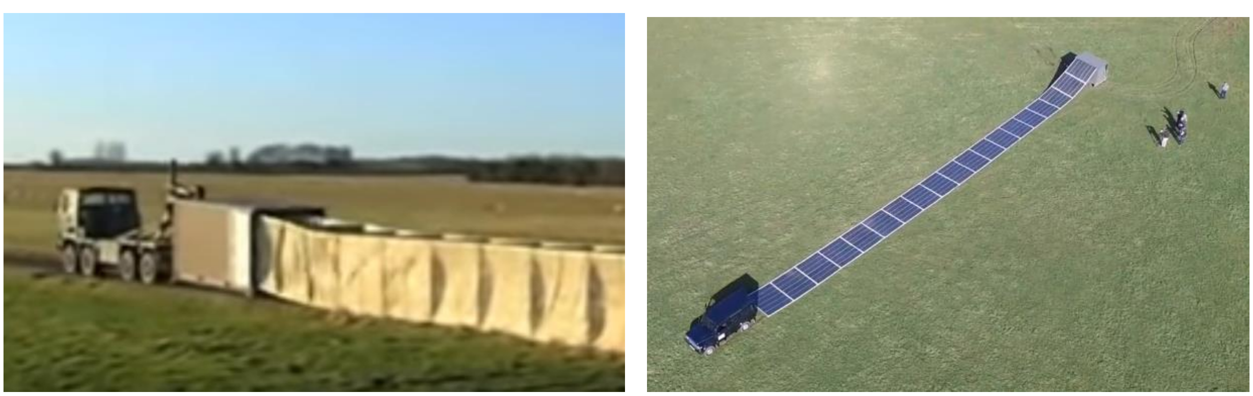

Figure 5-2 - (a) HESCO barrier deployment from a moving truck [61] and (b) Renovagen Rapid Roll T deployment [62].

To transport the receiver, existing shipping containers would likely be employed. Standard 20-foot ISO shipping containers or their sub-divided derivatives could be used: bicons, tricons, or quadcons. For air transport, the standard 463L pallet system would allow effective usage with existing aircraft: C-5s, C-17s, and C-30s. The CV-22 Osprey might also be used. Future concepts might employ autonomous transport and deployment.

A military installation with a ground-based space solar receiver would likely need to take a similar approach to that required for deploying large-area thin-film solar. The receiver would probably need to rest on flat terrain or employ supporting structures. The receiver might need stakes or weights to ensure it is secure in high winds. Managing the deployment of a very large, thin material could require measures similar to those used with tarps and agricultural plastic designed to cover large areas. Additionally, the receiver would need to be kept clear of foliage, ice, dust, and other materials.

Measurements performed at low power levels have found significant microwave attenuation through trees and vegetation [63]. Dust buildup on a rectenna may lead to attenuation depending on the frequency selected, though it has been found that attenuation due to sand and dust was not significant below 30 GHz [64]. For optical wavelengths, clouds, water, or ice could attenuate the beam effectively completely under some conditions [65]. Similar to photovoltaic arrays for ground solar, photovoltaics for laser power beaming would be subject to a decrease in total power due to dust buildup [66]. Opaque items could create shadowing.

To avoid some of the atmospheric losses resulting from having a ground-based receiver, and to potentially allow the use of shorter wavelengths to decrease the required transmit area for the transmitter, high-altitude receivers have been proposed [67]. A high-altitude receiver could be stationed either below or above the clouds, depending on whether laser or microwave power beaming were to be used. The power could be used by aircraft at altitude, or be relayed to the ground via power beaming, a tether, or other means. Addition of another power beaming link could be employed as suggested by Dickinson, but would introduce additional inefficiencies [50]. Surveillance aerostats employing tethers have been used by the U.S. in remote places like Afghanistan [68]. An airship with a receiver, connected to the ground via tether could be employed for space solar, but might pose a hazard to aviation operations. Additionally, airships could be more vulnerable to attack or could reveal the location of the receiver. Mission scenarios could dictate whether costs, decreases in efficiency, and the possible aviation hazard would justify reducing the required area on the ground.

5.6 Review of Concepts

About two dozen space solar implementation concepts were reviewed for suitability for adaptation for providing power to a remote installation with a limited receiver area. They are listed in Table 5-3, and described in more detail in Appendix D. Depending on the particulars of the implementation details for each, they may or may not be appropriate to provide the transmit side for the tactical power beaming links outlined above, or even for larger strategic situations. Many of the concepts do not appear to have sufficient technical details available, and have not been developed to a level that permits meaningful comparison among concepts, or lack credibility because of apparently unrealistic system parameters. Because of this, comparisons for total system mass, cost of power, and other major parameters were necessarily crude. Likewise, only a limited empirical basis for making extrapolations for major subsystem performance exists today. To construct the cost basis for comparison, mass-specific power [69, pp. 84-85] was used as a principal input. Anticipating that a practical solar power satellite would almost certainly need to be made out of mass-produced modules to minimize costs, a case can be made for lower per unit mass costs than historically demonstrated by space systems.

Table 5-3 – A Selection of Some of the Space Solar Concepts Considered

1968 - Glaser SPS	2010 - Solaren SSP
1996 - SPS2000	2012 - Lew Fraas Orbiting Mirrors
1997 - SSP SolarDisc	2012 - Solar High update of 1979 DOE/NASA Ref SPS
1997 - SunTower	2013 - Laser GEO Beaming to Relay Aerostat
1998 - Integrated Symmetrical Reflector (ISC)	2014 - Hyland Power Star
2000 - Abacus/Reflector Solar Array	2015 - CAST Multi-Joints SPS
2004 - Mitsubishi Solarbird SPS	2015 - Lunar Tin Can SPS
2008 - JAXA MPT SPS (aka JAXA 2004)	2015 - SPS OMEGA
2008 - JAXA Solar Pumped Laser	2015 - Sunflower Thermal Power Satellite
2009 - Aerospace Corp. (Large Modular Laser)	2016 - SPS-ALPHA Mark-I & II
2009 - Aerospace Corp. (Small Laser)	2017 - CASSIOPeiA Solar Power Satellite
2009 - LLNL Solar Power Beaming (Laser)	2018 - Update of Northrop Grumman / Caltech SSPI
2010 - EADS Astrium (Laser)	

Abbreviations: CAST = China Academy of Space Technology; EADS = European Aeronautic Defence and Space; GEO = geosynchronous orbit; IR = infrared ; ISC = ; JAXA = Japanese Aerospace Exploration Agency; LLNL = Lawrence Livermore National Laboratory; SPS = solar power satellite.

Receiver Regions

To explore the impact of a range of receiver locations on notional constellation designs, the DRRs examined were expressed as specific latitude-longitude locations, and are summarized in Table 5-4. The latitude of the receiver is relevant to orbital constellation design, but longitude generally is not, excluding geostationary and other specialized orbits. Atmospheric characteristics of the locations (driven by altitude, climate, and weather) will affect power beaming performance, depending on the frequency selected.

Table 5-4 – Parameters of Design Reference Regions (DRRs)*

Design Reference Region	Location	Lat (°)	Long (°)	Elevation (m)
DRR1	Solomon Islands	-9.4	160.2	100
DRR2	Greece	36.4	25.4	100
DRR3	Afghanistan	33.2	69.6	2,200
DRR4	Somalia	9.5	49.1	410
DRR5	Colombia	2.0	-72.0	200
DRR6	Alaska	65.6	-167.9	270
DRR7	Syria	36.2	37.2	380

*The three DRRs shown in green are representative for others at similar latitudes.

Orbits

For assessing the impact of orbit selection on system performance, an initial review of the 12 orbits shown in Table 5-5 was performed. The orbits were selected based on parameters such as altitude, inclination, and eccentricity. They are intended to span the trade space of relevant parameters while providing a representative sample of combinations. Actual operational orbits might differ for reasons including the availability of the orbit or orbital slot, regulatory issues involving the International Telecommunications Union and other agencies, and space radiation constraints.

Table 5-5 – Possible Orbits Considered

Orbit Description	Apogee Altitude (km)	Perigee Altitude (km)	Inclination (deg)	No. Orbits/Day	Period (min)
LEO	500.0	500.0	28.5	15.2	94.6
Sun Sync Repeat 1	1,676.5	1,676.5	102.9	12.0	119.9
Low MEO	2,158.6	2,158.6	28.5	11.0	130.8
Sun Sync Repeat 2	2,158.6	2,158.6	105.9	11.0	130.8
Sun Sync Repeat 3	2,719.9	2,719.9	110.1	10.0	143.9
Sun Sync Repeat 4	3,383.6	3,383.6	116.0	9.0	160.0
HEO Elliptical	7,414.0	963.0	116.6	8.0	180.2
Low Van Allen Gap	7,000.0	7,000.0	55.0	5.6	256.7
High Van Allen Gap	12,000.0	12,000.0	55.0	3.5	413.2
Molniya	39,850.5	500.0	63.5	2.0	717.7
GPS	20,200.0	20,200.0	55.0	2.0	718.7
GEO	35,786.0	35,786.0	<1	1.0	1,436.1

Abbreviations: LEO = low Earth orbit; MEO = medium Earth orbit; HEO = high Earth orbit; GPS = Global Positioning System; GEO = geosynchronous Earth orbit.

Low orbits have numerous disadvantages: shorter access times to receivers, larger numbers of satellites required for comprehensive coverage, limited lifetimes due to drag, potentially large percentage of time in shadow (which could likely not be addressed with onboard storage due to mass constraints), and greatest risk of space debris hazards. These factors were deemed to outweigh the advantage of less lengthy power beaming links, so LEO was eliminated from extensive consideration. A number of sun-synchronous orbits were examined, with a representative one in low medium Earth orbit selected for detailed analysis. Twelve-hour highly elliptical Molniya orbits have proven successful in providing communications to high latitudes, but lower altitude elliptical orbits offer similar benefits with a shorter range, benefitting power beaming links. Orbits like those used by O3B [70] or GPS [71] might strike a good balance between power beaming link range, eclipse time minimization, and coverage; though a constellation would be required to provide continuous service to a given site, and the radiation environment is harsher than alternatives. This potential for balance drove the selection of 20,000 km for several of the power beaming links analyzed. Although it was the farthest orbit considered, GEO offers the considerable benefit of constant ground coverage, albeit over a fixed but large sector of the Earth. However, power beaming from GEO would suffer significant cosine and atmospheric path losses at higher latitudes, and off-nadir longitudes. The detailed analysis of the orbits and constellations is shown in Appendix K. Other orbits or variations on the orbits listed are possible, such as an inclined geosynchronous Laplace plane orbit, which has reduced station keeping requirements [72].

Results of the Space Solar Architecture Development Process

The analysis shown above can be extended to large satellite constellations. The orbital constellation development process is indicative of how effectively a constellation of SPS platforms can serve any given installation within a region, constrained by latitude and longitude. However, the constellation may not necessarily be able to serve every site within the region simultaneously; that will depend on the total number of sites, their power requirements, and the number of satellites in the constellation.

6 COMPARISON OF ALTERNATIVES

Military operations require energy in a variety of forms for different purposes: lethality, mobility, mission support activities, and base support activities. Of these, the last two are predominantly in the form of electricity, though inroads are being made in the first two with the advent of practical directed energy weapons systems, railguns, and hybrid and electric vehicles. For this comparison of alternatives, only sources for producing electricity are considered, acknowledging that some military energy needs will only be satisfied with liquid hydrocarbon-based fuel or other non-electrical energy forms for the foreseeable future. This is driven by the high energy density of liquid hydrocarbon-based fuels and other sources, and the proliferation and expected lifespans of existing systems, many of which are expected to extend well beyond ten years.

6.1 Existing Paradigm: JP-8

The use of Jet Propellant 8 (JP-8) fueled generators ostensibly enables the DOD to operate with a consistent battlefield fuel, simplifying logistics. Additionally, generators have been shown to operate at relevant environmental extremes while providing a mobile battlefield power supply with excellent power quality and high reliability. These systems also meet specifications for surviving electromagnetic pulse, nuclear, biological, chemical attacks, and maintenance requirements. However, dependence on JP-8 could limit combat power, because of projected increasing energy demand, associated fuel costs, and the potential inability to re-supply under fire.

Diesel fuel generator systems are vulnerable to denial of fuel supply lines by adversaries and host country politics. Using the fuel consumption of the MEP-PU-810A JP-8 generator (60 gallons per hour to yield 840KW output [73], shown in Figure 6-1) as a benchmark, more than half a million gallons per year are required for continuous operation at the rated load. According to the 2009 AEPI causality factors report for Afghanistan [74], one convoy of 16 supply trucks carries nearly 100,000 gallons of fuel, and resupply activities resulted in one casualty for every 23.8 fuel resupply convoys. This implies that about one casualty can be expected per year for every five MEP-PU-810A JP-8 generators in continuous operation at the rated load.

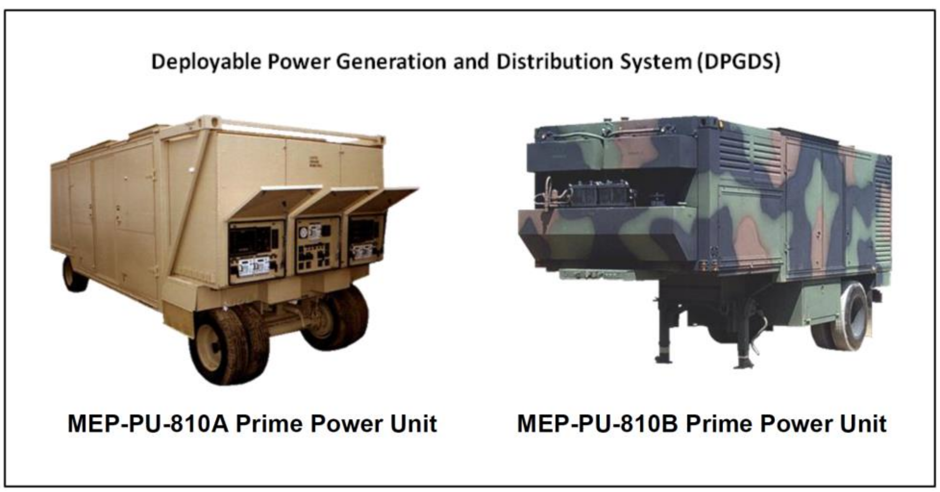

Figure 6-1 – The MEP-PU-810 generator, rated for 840 kW output, consumes 60 gallons (180 kg) of JP-8 per hour [75]

In spite of measures to improve fuel efficiency, an increase in the energy demand is projected because of the expanding use of command, control, communications and information systems, un-crewed systems, and eventually, directed energy weapons [76]. Figure 6-2 shows the increase in fuel consumption over time. Conflicts from WWII through Operation Enduring Freedom, and the increasing numbers of gallons required per U.S. soldier per day are also shown indicating the increasing role energy has on the battlefield. As shown on the chart, future fuel consumption is projected to rise steeply in the worst-case scenario to provide additional combat capability. If JP-8 is used to meet this increasing energy demand for the battlefield, it will be necessary to manage and protect a larger fuel supply chain. This results in potentially increased combat personnel or contractor requirements and higher casualty rates. Total costs will increase, including those associated with delivering the fuel.

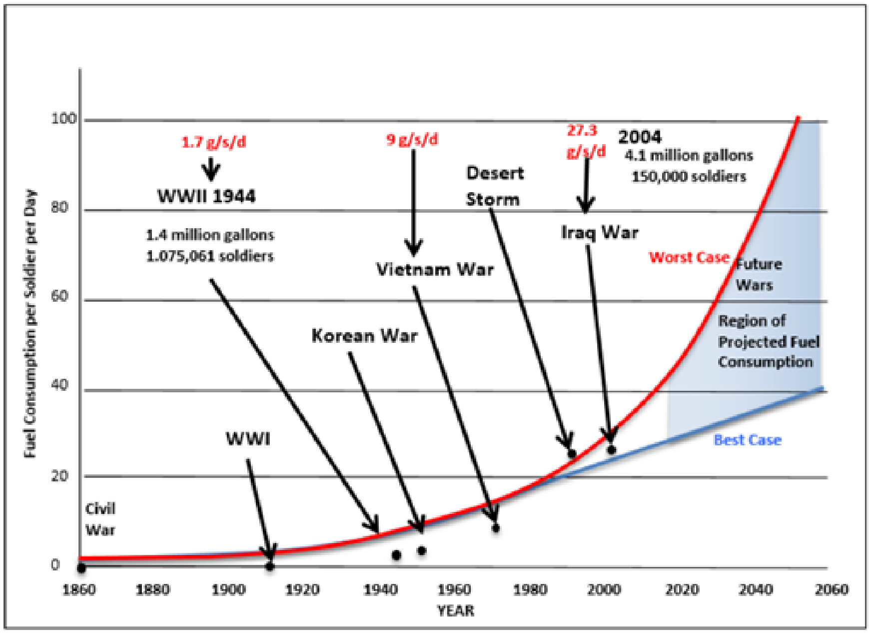

Figure 6-2 – Projected military fuel consumption for best and worst cases. g/s/d = gallons/soldier/day. Adapted from [77].

6.2 Selected Alternatives

To assist in evaluating different approaches to meet the military's energy demands, energy concepts in addition to space solar are described below. It is probable that a portfolio comprised of different alternatives might provide the greatest resilience in a given mission situation.

Hydrogen (H_2) Fuel - H_2 has been proposed as a future fuel as it can be manufactured from a number of sources [78]. It has significantly different production, transportation, and storage requirements than conventional fuels and requires fuel cells to use the energy. Fuel cell technology has an extensive history but has yet to reach the cost and maturity thresholds needed for widespread adoption by the DOD and elsewhere.

Synthetic Fuels - Commercially proven technologies that generate synthetic fuels with resources such as coal or biomass are available. These fuels could likely be used with existing JP-8 power sources with modifications. Experiments have also been done to convert seawater into usable jet fuel, at fairly low costs, though this approach is energy intensive [33].

Ground Solar - Ground-based solar technologies are increasingly prevalent as a supplemental power source to fuel-consuming generators, as they help reduce fuel demand. They can also be used with batteries in a hybrid configuration. The power density available varies based on location, time of day, season, and weather. Although silent, it may present a large potential target for adversaries.

Very Small Modular Reactors (vSMRs) - An alternative that has regained attention in recent years are very small modular nuclear reactors), also called mobile nuclear power plants (MNPPs). A relatively favorable assessment in the 2016 Energy Systems for Forward Operating Bases Defense Science Board (DSB) report brought renewed interest, and a subsequent report continues to build the case [79]. However, experts have pointed out that decades of previous efforts and optimistic assessments with regards to small nuclear have yet to come to fruition [80], and vSMRs appear ill-suited for power installations requiring less than megawatt levels [19]. In addition, some countries have restrictions on the use of nuclear power, or additional processes for visits by nuclear-powered ships, which might complicate deployment, operation, and transport of vSMRs in certain situations. Australia is one such country [81].

Others - Options like wind, hydro, tidal, geothermal, and others might supplement power for military operations, but because of their locale dependence and variability were not deemed relevant for further consideration.

6.3 Comparison Points

Due to the difference in technology readiness between space solar and existing and proposed alternatives, comparisons risk being meaningless or highly speculative due to implementation uncertainties. With this caveat in mind, tabulated below are guidelines for some of the key comparison points**. Energy sources that don't require refueling will have an ever-increasing advantage from a logistics standpoint, once the break-even point for the cost of bringing initial system mass into theater is past.**

Table 6-1 – Comparison of remote installation energy alternatives

	JP-8	H_2	Synfuel	Solar	vSMR	SPS-RF	SPS-Laser
TRL	9	8	8	9	6 [19]	5	4
Cost to prototype	N/A	N/A	N/A	N/A	>$100M [19]	>$1B [1]	>$1B [1]
Needs Refuel?	Yes	Yes	Yes	No	No [2]	No	No
Power Density (W/m^2)	200-12,000 [82], [83], [84]	~17,000 [85]	200-12,000 (same as JP-8)	2-30 [86], [43]	6,400-16,000 [19]	10-90 [3] [36], [54]	10-700 [3] [37]
Minimum Size (W)	500W [87]	200W	500W (same as JP-8)	<1W	1 kW [88]	<1W [4]	<1W [4]

vSMR = very Small Modular Reactor, SSP-RF = Solar Power Satellite – Radiofrequency, SSP-Laser = Solar Power Satellite – Laser
[1] cost estimate using power beaming link assumptions and estimates for contributing cost factors
[2] reactor needs to be refurbished approximately every ten years, implementation dependent
[3] **limited by power density safety limits, not technology. High altitude receiver systems or those with integrated interlocks could be higher, but both have yet to be meaningfully demonstrated.**
[4] low utilization of space solar will increase relative power cost because of the large capital investment

Further comparison points and areas for investigation include those listed below, though some depend on prototyping or increased technology maturity before meaningful conclusions could be drawn:

- Costs beyond R&D to first prototype:
    - Levelized capital
    - Levelized fixed operations and maintenance
    - Levelized variable operations and maintenance
    - Disposal/decommissioning
- Mobility/Setup time
- Vulnerability/Availability
- Scalability

7 KEY FINDINGS AND RECOMMENDATIONS

The study team concludes that a coordinated development effort to advance the underlying technologies for space solar should be pursued, particularly for power beaming technology. The effort should execute demonstrations of increasing capability and sophistication, as outlined in this study's detailed recommendations. As these underlying technologies further mature, the viability of space solar as means for military energy supply should be reassessed regularly by tracking progress and trends of these four metrics: space transportation cost ($/kg), space hardware cost ($/kg), specific power of the space segment (W/kg), and the cost associated with the receiver segment ($/kWh). In addition, the progress of technologies that address the challenge of establishing power densities with military utility while maintaining safety should be tracked.

7.1 Key Findings: Opportunities

There are important categories of opportunities associated with the pursuit of development of a space solar for remote installations capability. They include:

(1) *Realization of technology dividends.* The dividends for DOD and the nation resulting from pursuing the technologies needed for space solar have considerable value in their own right, even if space solar is never implemented. These technologies include power beaming, solar energy collection, space robotics, in-space transportation, and energy conversion and storage.

(2) *Pathfinding of future military architectures*. Space solar and power beaming technologies unlock tantalizing future architectural possibilities for autonomous and distributed systems, and for novel intelligence, surveillance, and reconnaissance capabilities. These have direct bearing on the National Defense Strategy theme of lethality.

(3) *Establishment of U.S. leadership.* The opportunity exists for the U.S. to become the leader in relevant technology areas given relatively modest research and development investments, and offers prospective benefits not just for defense, but also for diplomacy, development, and domestic economic growth. This supports the National Defense Strategy theme of strengthening alliances.

7.2 Key Findings: Challenges

The challenges facing space solar development and deployment can be categorized in part using the project management feasibility construct known as TELOS: an examination of Technical, Economic, Legal/Political, Operational, and Schedule elements. Other similar assessment methodologies exist, such as PEST and PESTEL (Political, Economic, Social, Technical, Environmental, and Legal), but the means by which challenges might be categorized is necessarily somewhat subjective, and any given challenge might be appropriately associated with more than one category. Though challenges are presented in order of TELOS, categorizations may be overlapping.

Technical Challenges:

(1) *Mass specific power needs to increase.* For at least the next decade, materials to build solar power satellites would likely be launched from Earth. Correspondingly, space transportation will be a major cost driver. The amount of power that can be provided on Earth per unit spacecraft mass directly affects how much mass needs to be emplaced. Currently, relevant hardware prototypes have demonstrated transmitted power less than 10 W/kg, which is at least an order of magnitude lower than what is likely to be required [69] [89].

(2) *Minimal prototyping.* With few exceptions, hardware to validate the functional elements specifically for space solar has not been produced in the United States. In particular, little has been done to demonstrate power beaming at the distances and power levels required, with perhaps the most recent relevant demonstration having occurred in 1975, when 35 kW was transferred over 1.5 km [90]. Military usage of space solar would almost certainly require the development of a tactically deployable power receiver to satisfy operating and transport requirements. No work of significance in this area has been done to date.

(3) *Immaturity of potentially enabling technologies*. Besides power beaming, there are several areas that are critical to the viability of particular implementations of space solar, likely to include: high-volume producible, high-efficiency, space-rated photovoltaics; large space structure flatness/rigidity knowledge and control/compensation; and a host of others dependent on the proposed architecture, such as effective high voltage power management in space, thermal management, large area reflectors, and many others.

(4) *Unprecedented area-to-mass ratios for space structures.* The 1,368 W/m^2 available nearly continuously in space near Earth's orbit is significant, but to reach megawatt levels of power available for use on the ground after projected conversion inefficiencies will still require enormous areas for collection, regardless of the means of conversion and transmission used. For effective transmission in the microwave region, similarly large surfaces will be needed. In each case, the imperative to keep mass as low as possible for cost reasons will likely result in unprecedented area-to-mass ratio structures, presenting challenges for pointing and station-keeping. The challenges arise from the influence of the solar wind and from material rigidity and strength limits.

(5) *Uncertainty associated with operating lifetimes and serviceability*. Given the large expected capital investment required, it may be important for the space segment to operate for many years, perhaps in excess of typically demonstrated spacecraft lifetimes. Capabilities for servicing and upgrading of spacecraft have been developed and are advancing, but are not yet at the level of sophistication likely required. Reliable long-term operation of electronics and photovoltaics in space radiation and space weather environments could be difficult to achieve.

Economic Challenges:

(6) *High capital and development costs*. The ultimate investment required to implement a practical space solar system would likely be measured in billions of dollars. This is driven primarily by launch, in-space transportation, hardware production, and research and development costs. Though there are downward cost trends in some of these areas, system deployment affordability remains a primary obstacle.

(7) *Energy cost uncertainty*. The likelihood that the cost of energy from space solar will ultimately be competitive with alternate sources, even for the high energy cost scenarios often faced by DoD, is challenging to forecast given the uncertainties inherent in the technological development of both space solar and the alternatives.

Legal/Political Challenges:

(8) *Spectrum is not allocated for RF power beaming*. For a space solar system transmitting power via microwaves, a frequency assignment for power beaming by the relevant authorities is needed. These may include the International Telecommunications Union, the National Telecommunications and Information Administration, and the Federal Communications Commission. Although attention has focused on the industrial, scientific, and medical radio bands (e.g., 2.4 GHz-2.5 GHz and 5.725 GHz-5.875 GHz), the power densities likely to be involved are not strictly compatible with these frequency ranges. Currently, there is not an International Telecommunications Union service under which power beaming explicitly falls. The process of identifying and allocating spectrum takes many years and is not straightforward. Only the Japanese are executing meaningful activities in this area [91]. Many of the RF frequencies considered for space solar (5.8 GHz, 35 GHz, 94 GHz) are in use at military airfields around the world, complicating the situation for many remote installations.

(9) *Safety and perceptions of safety*. Though space solar systems could be designed to conform to existing accepted safety limits, in many cases this would diminish the utility of such a system. Even if the system is designed, deployed, and operated in an inherently safe manner, there may still be public perceptions of hazards, regardless of the portion of the electromagnetic spectrum used for power beaming. These present potential legal, political, and geopolitical challenges.

Operational Challenges:

(10) *Balancing incident power density (power per unit area, W/m^2) for safety and utility.* For a space solar system to be viable in many military operational contexts, the power density of the beam would likely need to exceed the human and ordnance safe operation levels set forth by the IEEE and other organizations. Although the safety thresholds are not necessarily hard limitations, the large disparity between the power densities provided by existing alternatives like JP-8 makes it difficult to close the gap without raising concerns about weaponization. Working within the higher power density limits adhered to by existing radar and directed energy systems opens up the trade space, but presents human safety and electromagnetic compatibility hazards, and may require relatively larger space structures for power collection and transmission.

(11) *Incompatibility with current basing paradigms*. Fundamental physical limitations inherent in existing base footprints and required power density levels for effective energy resupply necessitate difficult tradeoffs among safety, complexity, and availability. These factors, combined with minimum costs, suggest that space solar using microwave transmission is unlikely to be appropriate for locations requiring comparatively small amounts of energy or for locations with limited area for receivers. Laser power beaming and novel architectures could address or mitigate some of the concerns.

(12) *Mature alternatives.* In addition to the lower cost of implementing existing options, these options enjoy high technology readiness and boast demonstrated tactical value and heritage, having put their own costly and lengthy development cycles behind them. Displacing these proliferated incumbent technologies would require a compelling motivation and a sufficiently developed

replacement. It can be realistically expected that mature technologies will also exhibit at least modest improvements.

(13) *The possible emergence of mobile nuclear.* Though alternatives like contemporary mobile nuclear power plants are still in development, they likely require considerably less capital investment than space solar to become operational. Despite important questions about safety, implementation, political palatability, and operational usability, the mobile nuclear alternative cannot be ruled out as a viable potential power source for remote installations, as evidenced by historical [80] and present day examples [92]. Combining power beaming technology with mobile nuclear power plants is especially attractive, in that it leverages the high power density and minimal refueling requirements of nuclear with the flexibility and resilience of power beaming. However, even if paired with power beaming, nuclear would not be able to provide the global redirectability promised by most space solar architectures.

(14) *Susceptibility to attack.* Though a potential benefit of space solar over the status quo is the reduction of the logistics tail involved in delivering energy to forward locations, and consequent increased safety of personnel, a solar power satellite and receiving station could present vulnerabilities. Though the satellite would not be as susceptible to attack by non-state actors, concerns are growing over space becoming a contested domain, with "foreign powers deploying advanced 'counter-space' technologies" [93]. Recent trends suggest that there is limited support for the procurement and usage of expensive and potentially vulnerable large space assets [94]. Large solar power satellites could carry extra risk. This problem is not unique to space solar, and requires further review. Risks might be mitigated with approaches employing constellations of large numbers of smaller solar power satellites, rather than small numbers of large ones.

(15) *Space environment hazards.* Radiation, temperature extremes, solar activity, micrometeorites, and space debris are all potential challenges for space solar. Though today's satellites effectively contend with these hazards to operate successfully, the scale of most proposed space solar implementations may present additional unexplored risks.

Schedule Challenges:

(16) *Long development timeline*. Because of the need to more clearly ascertain the most attractive architectures for remote installations, to mature the required technologies, and the inherently long delivery schedules associated with most space projects, it is likely that a fully operational capability would not be fielded for at least a decade. In this respect, it may share some similarity with the development efforts for the capital-intensive Global Positioning System (GPS), which took almost 30 years to become fully operational, though there are important differences in the applications and the environment in which it was created. Space solar on large scales is likely to require a much greater amount of mass to be put into space unless extraterrestrial materials are employed, and such technologies have yet to be demonstrated. Absent a politically-driven engineering effort on the scale Apollo moonshot program, a protracted development timeline seems assured for a full system. However, many near-term transition and deployment payoffs that address existing needs, requirements, and gaps are realizable through spiral development in several technology areas, particularly power beaming; hence the first recommendation in the next section.

7.3 Recommendations

Given the findings presented above, the study team presents the following recommendations:

(1) *Mature space solar's functional technologies and develop advanced concepts, particularly for power beaming*. DoD should expand efforts in supporting the maturation of power beaming technology, taking advantage of existing investments in directed energy, and advancing both terrestrial and spaceborne power beaming. This effort should be led under the office of Under Secretary of Defense for Research and Engineering, through the Operational Energy Capability Improvement Fund (OECIF), with engagement from the Office of Naval Research, the Directed Energy Directorate of the Air Force Research Laboratory, DARPA's Tactical Technologies Office, the National Aeronautics and Space Administration, and similar entities. Power beaming has yet to be demonstrated at the distance, efficiency, or power level required for space solar. In addition to power beaming technology, key areas for development include in space solar collection, architecture analytics, and integrating technologies. **Technology areas and specifics are described Appendices A and B.**

(2) *Monitor and maintain parity with foreign developments*. DoD should monitor the progress of others in relevant areas to avoid technological surprise, and to reduce the chances of being faced with a breakout capability. Specifically, this effort should fall to the National Air and Space Intelligence Center, the Missile and Space Intelligence Center, and the Office of Technical Intelligence, as identified in the National Defense Strategy [95]. The PRC is seeking ascendancy in many ways, including through military modernization and advanced technology development. The PRC announced its plans to build a solar power satellite in GEO by 2050, starting with the first space demonstrations in the 2020s [4, p. 81]. The Chinese believe "whoever obtains the technology first could occupy the future energy market." [ibid.]. Space solar and power beaming have received considerable attention from many quarters: government, industry, and academia are working in concert to lay the foundation for the technologies needed [4, pp. 83-84].

(3) *Advance in-space assembly and manufacturing technology*. DoD and other U.S. agencies should continue to advance technologies related to space robotics and in-space assembly, via missions like those being executed by DARPA [96] and NASA [97]. Because of the sizable amount of mass required, and the likely inability to deploy on a single launch more than the smallest space solar capability, space robotics and in-space operations will be key enabling technologies. They involve highly sophisticated software, control systems, and algorithms, which are time-consuming and challenging to develop. Because these technologies have broad application even beyond the development of solar power satellites, investments in their advancement will yield dividends in areas as diverse as astronomy, intelligence, and space industrialization.

(4) *Address regulatory hurdles*. The DOD Chief Information Officer, the National Telecommunications and Information Administration, and the Federal Communications Commission should facilitate the existing efforts of industry in regards to regulatory concerns, such as those related to spectrum identification for power beaming.

(5) *Track progress regularly*. Because of the rapid recent pace of innovation and technological developments including regular launcher reuse [98] and true satellite mass production [99], DoD should reassess on a regular basis, perhaps biennially, the technical progress towards space solar and other options for military energy resupply using the metrics identified in this study, and following the guidance in Appendix P.

(6) *Strengthen partner relationships*. Per the National Defense Strategy, the U.S. Government should pursue the opportunity of space solar technology development as a means to strengthen partnerships

between defense and civilian agencies, and with international partners who are leading in specific areas (e.g., Japan, for microwave and laser power beaming technology).

7.4 Concluding Thoughts

History is built on contingencies, and it has been shaped in both clear and subtle ways by our evolving energy needs and sources. Energy technology has always been of profound importance for military and remote operations. This has been manifest as energy sources and means of transport have progressed on land from foot, to horse, to mechanization; at sea from sail, to steam, to coal, to oil, to diesel, to nuclear; and in the air from gasoline, to avgas, to jet fuel. As new domains of warfare emerge in space and elsewhere, the energy and technologies needed to secure and maintain dominance within them must be developed as well. The prospects for space solar hold both compelling opportunities and formidable challenges, each of which will be illuminated first by those that move decisively and proactively.

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APPENDIX A – TECHNOLOGY AREA GAPS

Some of the component technologies required to achieve space solar for remote installations have been matured to an extent in other systems, including communications satellites, radar satellites, directed energy systems, and others. However, major challenges remain in certain technology areas, and in the further maturation and implementation of both new and existing technologies at the scale required for usable space solar. In some technology areas, significant government and industry development efforts are planned or already under way. In others, existing investments are essentially nonexistent or insufficient. In these latter areas, a focused government research and development campaign is likely to yield the largest dividends.

To provide guidance as to where limited resources can be applied to reap the maximum benefit, the following gaps are categorized in three groups per the direction of the Operational Energy (OE) Capability Improvement Fund (OECIF), which sponsored this study. The three groups are:

LEAD: DoD/OE must drive the advancement of this technology. It is unlikely the required technology advancements will occur elsewhere within other government organizations, commercial industry, or academia. Significant investment will likely be required.

SHAPE: DoD/OE should guide and collaborate with partners to focus commercial industry and academia on DoD needs to advance the technology in beneficial directions. Some investment is required to apply other government, commercial, or academic technology to DoD needs.

FOLLOW: DoD should leverage technology investments within other government organizations, industry, and academia. Maintaining technology cognizance enables DoD to engage partners when necessary and potentially influence investment strategies.

<u>Technology Areas DoD/OE to **LEAD**:</u>

Power beaming technology subsystem and integrated demonstration development. For the modalities of microwave, millimeter-wave, and optical, there are potent opportunities to increase the technology readiness levels of transmitters and especially receivers. By developing integrated demonstrations that require instantiating all elements in hardware, the acceleration of this game-changing technology can be achieved. While power beaming is an essential function for space solar, its dividends will enable and address countless other DoD areas and applications of interest.

Cheaper, more efficient, lighter space PV cells. Though terrestrial silicon PV cells are a commodity item, PV cells for space remain expensive and specialized. Efficiencies for available space cells have improved from over time, and are now approaching 40-45% in 2018 for complex, multijunction architecture devices for research cells[1]. These improvements are exceptionally important at the systems level because higher efficiency results in less waste heat and lower array temperatures. Currently, PV cells for space applications are not produced in the quantities or price points required for practical space solar. Emerging developments in hydride vapor phase epitaxy (HVPE) and perovskite cells may address these shortcomings. Research in these areas should be accelerated, and should include: exploration of high efficiency solution-processed perovskite tandems (>30%) for space; next level investment in HVPE for lower cost III-V manufacturing (for high efficiency multijunctions, starting with tandems); integration of emerging thin film batteries with thin film PV in single packages; and early and rigorous reliability, radiation, and accelerated testing studies that will leverage the expertise in terrestrial PV reliability and failure reduction applicable to larger scale manufacturing.

[1] https://www.nrel.gov/pv/assets/pdfs/pv-efficiency-chart.20181221.pdf

Architecture modeling, analysis, and concept development. During the course of this study, several areas of future investigation were revealed that were beyond the scope and resources of the study. These include higher fidelity modeling and simulation of space solar constellation operation concepts with specific receiver locations in a variety of distributions and configurations and modeling of mission-specific concepts of operations and campaign level scenarios that include prospective space solar assets. Additionally, since non-physical energy delivery through space solar and power beaming systems presents completely new archetypes that are not currently realizable or obvious, effort should be invested in exploring these possibilities and their implications.

Cheaper, more efficient "retina-safe" lasers and PV. A set of wavelengths longer than 1500 nm allows for safe power densities far exceeding those allowable at visible and shorter infrared, on par with peak sunlight. However, lasers and bandgap-matched PV in this safer region are not as affordable or efficient as at shorter wavelengths. Directed energy developments to date have not focused on this region and are unlikely to because it is not mission enabling. For power beaming and space solar, having a higher power density option in this spectral region could be revolutionary.

High-altitude power transmitter and receiver platforms. Many of the power density-related safety concerns of ground-based receivers might be obviated by using a suitable high altitude space solar receiver, but despite a number of proposed concepts[2], there has not been meaningful hardware development in this area. Elevated, tethered, and free-flying platforms have been used in the past by the Japanese[3] and Canadians[4] to successfully advance smaller-scale power beaming technology elements, and such configurations offer the opportunity to prototype system elements with beam geometries that are similar to those likely to be used for space solar. Refining transmitter and receiver technology to minimize mass for flight on high-altitude platforms would also improve the metrics needed to address space solar's economic challenges. Space solar-like capabilities might also be realizable with very high altitude stratospheric platforms, another area of recent interest. Though adding additional high-altitude conversion stages to a space solar architecture would present complexity and efficiency challenges, and may provide the enemy with another opportunity to attack, there may be a benefit to dramatically reducing the air mass that a link from space would need to traverse. Power received might be used at altitude by novel future airborne platforms, and with negligible atmospheric attenuation, the range of wavelengths usable for power beaming would be greatly increased. One application might be as a power receiver or coordination point for uncrewed autonomous assets, either at altitude or via tether or power beaming link suited for atmospheric transmission to the ground. Concepts and technology for these approaches have received only limited examination to date and may overcome some of the limitations of using an area-constrained ground-based receiver if aviation and other potential hazards can be effectively mitigated.

Deployable rectenna and laser PV arrays. Other than a small amount of conceptual material, there has not been meaningful development for the supporting elements for large-area, sky-facing rectenna arrays or laser PV receiver arrays. These would be a critical deployable element for nearly all space solar implementations. Without hardware development in this area, system cost estimates will have no meaningful empirical basis. Although rectenna receiver arrays have been demonstrated, they have generally been rigid, vertically oriented laboratory assets. There is a precedent for laser PV arrays with conventional solar arrays, but there are also key differences that have only received limited exploration, such as the effective conversion of

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[2] S. Blank, et al., "Feasibility Study of Space Based Solar Power to Tethered Aerostat Systems," in Proceedings of the 2013 IEEE Wireless for Space and Extreme Environments Conference, Baltimore, MD, USA, 2013

[3] T. Mitani, et al., "Microwave Power and Information Transmission Experiments from an Airship and a Study on Magnetron-Based Microwave Transmitting System Weight," 12th SPS Symposium, 13-14 November, 2009.

[4] http://www.friendsofcrc.ca/Projects/SHARP/sharp.html

what is likely to be incoming light of variable and inconsistent homogeneity. Creating a deployable receiver array for each of these modalities at a range of frequencies and wavelengths would clarify technical challenges for space solar and large-scale power beaming.

Power beaming, directed energy, non-lethal weapon, jammer, detection & ranging, and communications integration. Given the increasing proliferation and commonalities in microwave, millimeter wave, and laser systems, there are clear and potential opportunities for dual or multiple use systems that exploit the abilities to transmit, receive, and convert energy for different purposes. One such concept is the Flexible LAser System Concept (FLASC). The Active Denial System (ADS) in the millimeter-wave regime and other systems in the microwave regime may offer similar synergies. These opportunities need careful examination to leverage lessons learned and potentially refashion core technologies for diverse applications. On the receiver side, effort should be directed toward the investigation of the adaption of conventional solar photovoltaic arrays as power beaming receivers, and the combination and integration of rectenna receivers or laser PV in the same equipment to permit the collection of energy from a range of sources.

Technology Areas for DoD/OE to **SHAPE**:

Cheaper, more efficient, lighter, high-temperature solid-state devices. The solid-state electronics that are involved in many space solar concepts have advanced significantly in the past several decades. These directly feed one of the most important figures of merit for the space segment: mass specific power (W/kg). In the early 1980s, a solid-state device microwave amplifier typically had an efficiency (DC-to-RF) of about 20%-25%. By the early 2000s, that had increased to about 60%-70% efficiency. At present, solid state power amplifiers in the range of 70%-90% are becoming available. In the last decade, similar advances have been made in solid state diodes and fiber lasers. In each case, further increases in efficiency, cost, temperature performance, specific power, and reliability will benefit space solar, power beaming, and other applications.

Novel storage technologies. The need for quick-recharge capability and the possibility of extremely lightweight battery storage have important implications for power beaming receiver sites and space or airborne power transmitter assets.

Enablers for weight reduction. Additive manufacturing techniques, metal foams, advanced materials, and novel gossamer structures are some of the areas in which benefits may be attained in the reduction of system element masses while still achieving the required performance for strength and other qualities.

Advanced power delivery concepts. Initial examinations have been performed for concepts such as quantum energy teleportation and extreme range capacitive and inductive resonant coupling. If either of these or other prospects like revolutionary re-entry vehicle technology or ubiquitous micro autonomous drone delivery are realized, the landscape for space solar might be radically reshaped.

Technology Areas for DoD/OE to **FOLLOW**:

Launch cost reduction. Progress from SpaceX, Blue Origin, and other industry players appear as though they will have bearing on reductions in launch costs. Existing government initiatives, like the DARPA Launch Challenge also seek to address this critical element.

Advanced in-space assembly capabilities. Progress toward in-space robotic assembly is advancing, and has benefitted from research targeting terrestrial applications. Cooperative robotic systems have been demonstrated successfully that allow large and complex structural assembly by autonomous teams of free-flying helicopters. For space applications, Robotic Servicing of Geosynchronous Satellites, a major DARPA program, is creating a GEO-based capability for on-orbit inspection, repair, and maintenance. NASA is pursuing other programs, like Restore-L. For space solar, a spaceborne assembly capability that builds on the developments of these efforts is likely to be needed.

In-space transportation. Due to the probable role of in-space transportation from low earth orbit to space solar operational orbits, attention should be paid to developments in in-space transportation.

Space resource utilization and industrialization. Space solar may also be synergistic with other economic uses of space, such as extraterrestrial resources and space tourism. DoD/OE should follow the developments of other government agencies, countries, and commercial entities for the implications for space solar. There may be economic pressures that would precipitate space solar capabilities for the moon or Mars. If such scenarios developed, DoD might be able to act as a “fast follower.”

APPENDIX B – DOD/OE DEVELOPMENT PLAN AND ROADMAP

Power Beaming Advanced Technology (PBAT) Development Plan

To accelerate development of the foundational technologies and resolve architectural challenges for space solar, a multi-pronged investment approach is recommended. By addressing the functional elements of the system and investigating competing concepts and supporting technologies, critical advances can be made to effectively support ongoing DoD efforts in this area. For investment in preparation for advanced technology demonstrations of space solar capabilities, the following groups of areas should be considered, with efforts commencing in FY20:

(1) Space Solar Collection – Spaceborne optical trains, reflectors, and advanced space photovoltaics (PV) development are potential parts of an operational space solar system. Alternate PV chemistries and alternate manufacturing technologies may increase specific power while reducing total mass. Thermal, radiation, and space qualification testing for cells and modules employing these approaches will be needed.
(2) Power Beaming Transmission – New semiconductor technologies and microwave, millimeter-wave, and optical sources can drive down cost and mass in the transmitter in the space segment. Space qualification of many of these technologies has yet to occur.
(3) Power Beaming Reception – Development is needed for tactical deployable ground receivers at Forward Operating Bases for all power beaming modalities. High and low power density rectennas and tuned-bandgap PV are essential, as are integrated receiver ruggedization, portability, and modularity.
(4) Receiver Power Distribution – Integration into Forward Operating Bases, deployed microgrids, and with expeditionary force approaches is imperative for successfully utilization of space solar by DOD. Planning and constructing the paradigms for power distribution and utilization in present and future scenarios, with both staffed and autonomous users, is needed to ensure space solar's utility.
(5) Architecture Analytics - At the highest level, architectural analysis, modelling, and simulation is crucial to validate realistic DOD CONOPs. This will include the assessment of the suitability and implications of different means of emerging solar energy collection, power conversion, power beaming, orbits, and ground and space segment approaches.
(6) Integrating Technologies - Key prospective technologies development such as large area metrology, high-altitude receiver craft, thermal management, high voltage management, and airborne tether technologies.

For FY21 and beyond, advances in the areas above will clarify the path forward to demonstrate an integrated end-to-end capability. Starting at laboratory scale and building toward ground, elevated, high-altitude, LEO, and ultimately higher orbits, the progression of greater power beaming capabilities to include beam links and power over distance would provide a path to a deployed capability.

Taken together, these elements will enable efforts toward a practical space solar system to enhance energy systems for deployed forces and associated warfighter sustainability and lethality. Coordination and collaboration among U.S. government stakeholders such as NASA and the DOE will amplify the DOD investment.

APPENDIX C – SPACE SOLAR SYSTEM KEY PARAMETERS

A challenge in reviewing proposed space solar architecture concepts proved to be that they often omitted key parameters needed for meaningful review to assess their feasibility. With a relatively small set of quantitative information, it is possible to derive additional parameters of interest by applying physical and mathematical relationships. Presented below is a minimal set of information needed for a given proposed space solar architecture to be subject to first-order analysis.

1. Name of concept
2. Orbit(s) details
3. Solar collector size
4. Transmitter aperture size
5. Total spacecraft mass
6. Power beaming wavelength
7. Receiver aperture size
8. Power output from receiver
9. System cost estimate
10. Reference with description/depiction

These parameters allow for approximate values to be calculated for power densities, specific power, and areal specific mass. Ideally, a much greater set of parameters would be provided as well, including anticipated segment efficiencies, receiver mass, beam control approach, estimated operating lifetime, and economic factors assumptions.

APPENDIX D – SPACE SOLAR ARCHITECTURE CONCEPTS

This appendix includes a survey of several previously proposed space solar architectures, principally for utility grid power provision. Concepts are listed in approximate chronological order and begin in the 1990s.

Note: parameters and summaries are shown as represented in the referenced source, and have not been independently validated for feasibility in all cases. Sources did not always provide all parameters needed for adequate assessment.

SPS2000 (1996)

Organization: Japan SPS Working Group
Power Beaming (PB) Method: MPT @ 2.45 GHz
Power Delivered: 10 MW
Mass: 240 t
Orbit: Low Earth orbit (LEO)
Cost Estimate: $100 Million goal

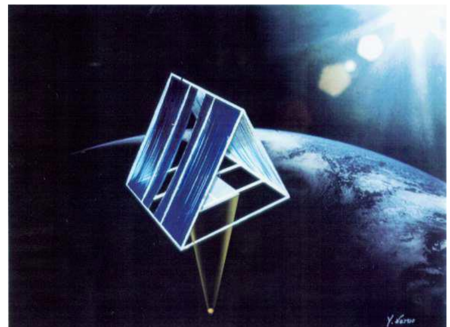

Figure D-1 - Artist's concept of SPS2000

The main goal of the SPS2000 (Fig. D-1) is to provide an affordable, practical alternative to many previous space solar power (SSP) concepts. The vehicle is stationed in LEO to reduce delivery costs and to scale down required components. The project then also can be relatively lightweight. A constellation of these satellites would be required to permit a constant stream of power to ground stations. The three sides of the satellite would roughly measure 300 meters × 300 meters, and a ground rectenna of 132 meters × 132 meters would be required.

Sources: www.spacefuture.com/power/sps2000.shtml. Accessed 2017-11-13 and "R&D of Solar Power Satellite and Wireless Power Transfer in Japan", Naoki Shinohara, Kyoto University, 2017.

SSP SolarDisc (1997)

Organization: 1997 Fresh Look Study
PB Method: MPT @ 5.8 GHz
Power Delivered: 1-10 GW depending on use
Mass: Varies
Orbit: Geosynchronous orbit (GEO)
Cost estimate: $30 billion to $50 Billion

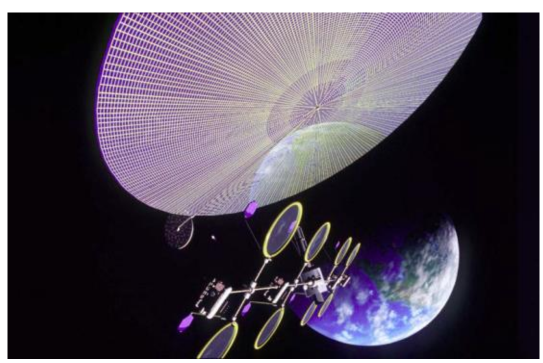

Figure D-2 – SSP solar disc

A main goal of the SSP solar disc concept (Fig. D-2) was to reduce the cost of a large GEO system. As market demand increases, strips could be added to the disc to increase its power delivery capabilities. The concept would be launched to LEO with a boost to attain GEO. The launch infrastructure would need to include robotic assembly of the concept in orbit. The ultimate goal would be to have a constellation of these satellites each with a solar collection disc of 3-6 kilometers in diameter. A transmitting array of 1 kilometer and a receiving array of 5-6 kilometers would be used.

Source: Mankins, John C. "A fresh look at space solar power: new architectures, concepts and technologies." *Acta Astronautica*, vol. 41, no. 4, 1997, pp. 347–359., doi:10.1016/S0094-5765(98)00075

SSP SunTower (1997)

Organization: 1997 Fresh Look Study
PB Method: MPT @ 5.8 GHz
Power Delivered: 100 MW-400 MW
Mass: Variable
Orbit: LEO to elliptical
Cost estimate: $8 billion-$15 billion

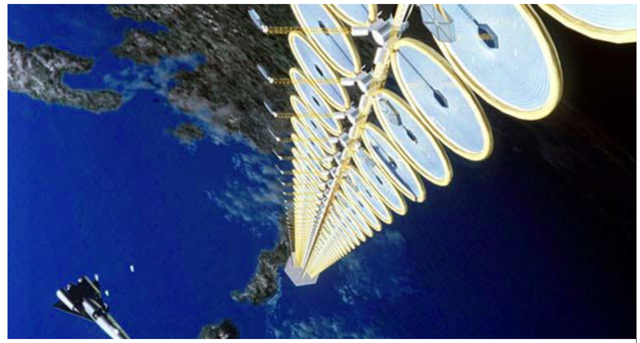
Figure D-3 – The SSP SunTower

The SSP SunTower (Fig. D-3) conceived to be modular and evolvable. The main tower would be designed to accommodate more additional collectors that could be launched in accordance with market demand. A constellation of these satellites would be required for continuous coverage. The satellite would be gravity-gradient stabilized in orbit. The overall vehicle would be comprised of an expandable array of solar collectors, each collector about 50-60 meters in size, spaced 100 meters apart from one another. The overall height could be as much as 15 kilometers. There would be a transmitting antenna of 300 meters in diameter that would transmit to a ground receiver 4 kilometers in diameter.

Source: Mankins, John C. "A fresh look at space solar power: new architectures, concepts and technologies." *Acta Astronautica*, vol. 41, no. 4, 1997, pp. 347–359., doi:10.1016/S0094-5765(98)00075

Integrated Symmetrical Concentrator (1998)

Organization: Whitt Brantley, NASA-MSFC
PB Method: MPT via RF transmitters
Power Delivered: 1.2 GW
Mass: 22,463 t (Launched) / 17,076 t (Orbited)
Orbit: GEO
Cost estimate: Unavailable

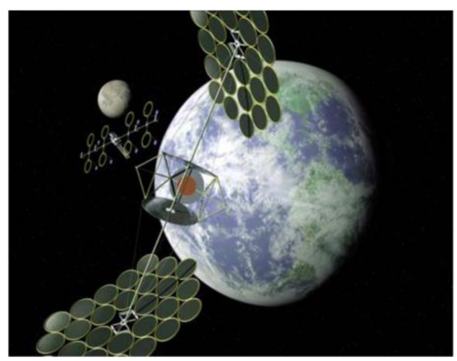
Figure D-4 – Integrated symmetrical concentrator

A 1998 study determined that power management and distribution masses were a significant portion of overall mass. In its integrated symmetrical concentrator concept (Fig. D-4), Whitt Brantley proposed the dual "clam shell" design to reflect incident sunlight to a location near the radiofrequency (RF) transmitters to reduce power management and distribution mass. The reflected light is then incident on photovoltaic (PV) arrays and the power converted to an RF signal.

Source: Oman, H. "Solar power from space new developments make it practical." *IEEE Aerospace and Electronic Systems Magazine*, vol. 16, no. 1, 2001, doi:10.1109/MAES.2001.894173.

ABACUS/Reflector Solar Array (~2000)

Organization: Connie Carrington, NASA-MSFC
PB Method: MPT via RF transmitters
Power Delivered: 1.2 GW
Mass: 29,261 t (Launched) / 22,183 t (orbited)
Orbit: GEO
Cost estimate: Unavailable

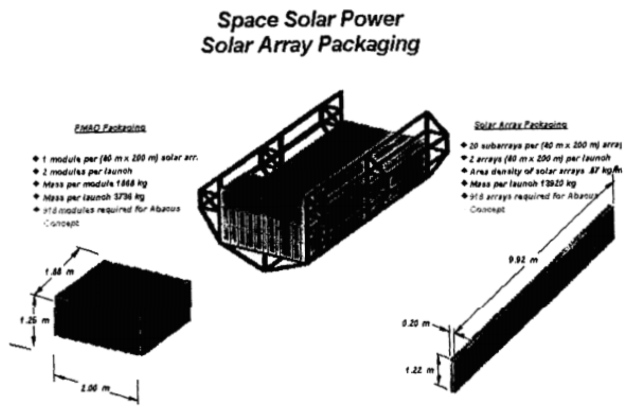

Figure D-5 – ABACUS Reflector, Solar Array

The ABACUS/Reflector Solar Array (Fig. D-5) is based on the integrated symmetrical concentrator (see above, Fig. A4) because it reflects incoming solar energy to the solar cell array, which is near the Earth-pointing antenna, where power is delivered to magnetrons. Precise control can position each mirror so that all the solar panels are constantly illuminated. The clam shell reflectors measure 3559 meters × 3642 meters. It was estimated 64 launches from reusable vehicles would be needed for construction.

Source: Oman, H. "Solar Power from Space: New Developments Make It Practical." *IEEE Aerospace and Electronic Systems Magazine*, vol. 16, no. 1, 2001, doi:10.1109/MAES.2001.894173.

JAXA SPS2004 (2004)

Organization: Japanese Aerospace Exploration Agency (JAXA)
PB Method: MPT @ 5.8 GHz
Power Delivered: 1 GW
Mass: 8,000 t
Orbit: GEO
Cost Estimate: Unavailable

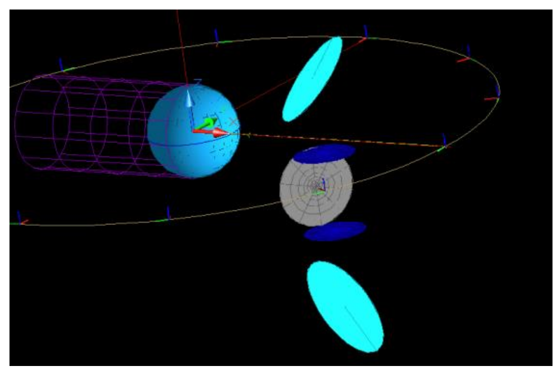
Figure D-6 – JAXA SPS2004

A distinguishing feature of the JAXA SPS2004 model (Fig. D-6) is its solar collection mirrors, which co-orbit with the PV array and transmitting antenna. This requires formation flying of the two mirrors and PV/transmitter where the mirrors can rotate to track the solar vector thus eliminating the need for rotary joints. The mirrors are 2.5 kilometers × 3.5 kilometers, the PV array of up to 2 kilometers, and a transmitting array of up to 2.5 kilometers.

Sources: "R&D of Solar Power Satellite and Wireless Power Transfer in Japan," Naoki Shinohara, Kyoto University, 2017, and Shinohara, Naoki. *Wireless Power Transfer via Radiowaves*. John Wiley & Sons, 2014. Print

Solarbird SPS (2004)

Organization: Mitsubishi Electric
PB Method: MPT via RF transmitters
Power Delivered: 1 GW total
Mass: 1000 kg per satellite
Orbit: LEO sun-synch
Cost Estimate: Unavailable

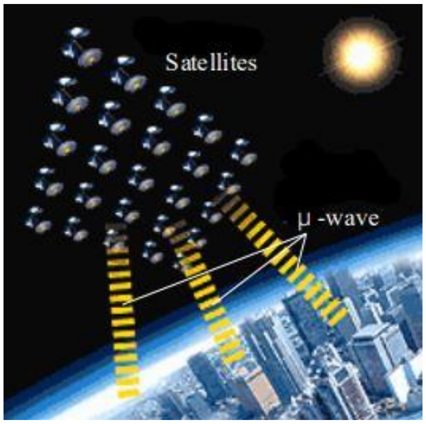

Figure D-7 – The Solarbird SPS

Unlike many other concepts, the Solarbird SPS (Fig. D-7) does not rely on a single transmitting SPS. Instead, Solarbird uses multiple smaller satellites to generate and send electrical power. By using at least 25 smaller satellites placed in orbit, the development of orbital assembly technology is not necessary. Additionally, as power demands increase, the number of Solarbird satellites can be increased to match.

Source: Ishii, H, et al. "Power Beaming Technology Demonstration Satellite for Solarbird Space Solar Power System." *Proceedings of the International Symposium on Space Technology and Science*, vol. 24, 2004, pp. 645-649

JAXA Sun Pumped Laser Concept (2008)

Organization: JAXA
PB Method: Laser
Power Delivered: Order of kW
Mass: 5,000 t
Orbit: GEO
Cost estimate: Unavailable

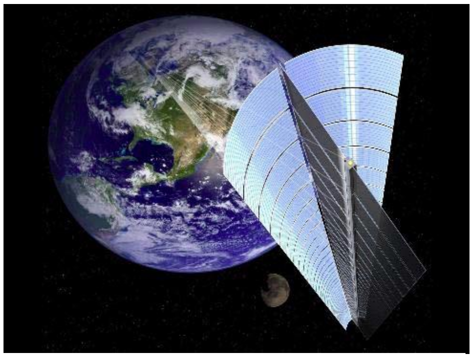
Figure D-8 – JAXA sun pumped laser

The sun-pumped laser concept is part of research by JAXA to create kW-scale SSP demonstration system (Fig. D-8). Efforts are focused on attaining a pointing accuracy of 0.1 micro-radians. This is done by having a beam steering control mechanism that combines both ground and space laser links. To account for atmospheric distortions of the pilot beam, the concept utilizes a fast steering mirror that can rapidly correct for the angular deviation. Ground tests seek to attain 1 micro-radian of beam steering, and develop laser technology to enable power transmission at 1070 nanometers on the order of 10s of kW.

Source: http://www.kenkai.jaxa.jp/eng/research/ssps/hmi-lssps.html. Accessed November 14, 2017.

JAXA MPT Concept (2008)

Organization: JAXA
PB Method: MPT @ 5.8 GHz
Power Delivered: 1 GW
Mass: Unavailable
Orbit: GEO
Cost Estimate: Unavailable

JAXA also has researched an MPT SSP concept (Fig. D-9) that could deliver 1 GW of energy. As with their laser concept, JAXA is focused on the precise beam pointing requirement that occurs when transmitting from GEO. For this concept, a ground receiver of 2 kilometers in diameter is anticipated. JAXA has demonstrated beam pointing control of 0.15º over approximately 50 meters.

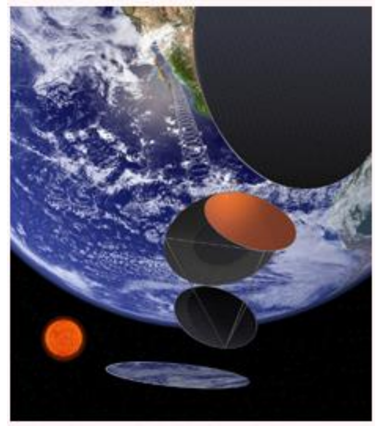

Figure D-9 – JAXA MPT concept

Source: http://www.kenkai.jaxa.jp/eng/research/ssps/hmi-lssps.html. Accessed November 14, 2017.

Solar Power Beaming Concept (2009)

Organization: Lawrence Livermore National Laboratory
PB Method: Laser @ 795 nm
Power Delivered: 1 MW
Mass: 9,125 kg
Orbit: LEO
Cost estimate: $500 million

Figure D-10 – Solar power beaming concept

The key element of the solar power beaming concept (Fig. D-10) is a highly efficient, electrical diode pumped laser developed at the Lawrence Livermore National Laboratory with a purported 50% electricity to light conversion efficiency with up to 70% optical-to-optical efficiencies. Another Lawrence Livermore National Laboratory technology is lightweight diffractive optics that can be packed into an efficient space. The concept would use an inflatable solar reflector. The laser wavelength is conducive to low atmospheric attenuation, and requires a relatively small receiving station. LEO orbit also reduces the cost and complexity of beam and optical system pointing and alignment requirements.

Source: Rubenchik, A.M., et al. "Solar Power Beaming: From Space to Earth." Lawrence Livermore National Laboratory, April 2009, LLNL-TR-412782.

Aerospace Corp Laser Concept (2009)

Organization: The Aerospace Corp.
PB Method: Laser @ 1 μm
Power Delivered: 1.2 GW
Mass: 29.7 t
Orbit: GEO Halo Orbit
Cost Estimate: Unavailable

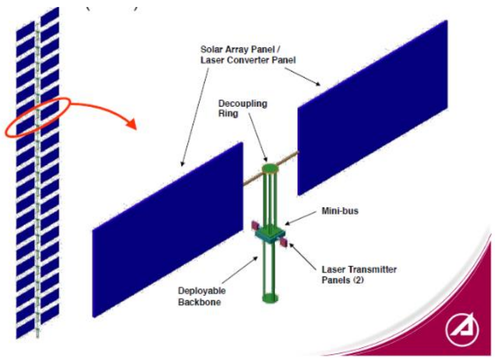

Figure D-11 — Aerospace Corp laser concept

As part of an SSP concept study, Aerospace Corp put together five SSP concepts all producing the same power delivery capabilities. Of the five concepts, the laser concept (Fig. D-11) was identified as the one with the most promise. The laser concept had the most promise as it allowed for the lowest mass system, had an extremely modular design for all subsystems, and spread the laser beam away from the ground site to mitigate ground safety issues.

Source: Penn, J., Law, G. "Future SSP Systems Concepts: the Laser Option – Commercial and Military Applications." *International Symposium on Solar Energy from Space*. 2009.

Aerospace Corp Military Concept (2009)

Organization: The Aerospace Corp
PB Method: Laser @
Power Delivered: 200 kW per satellite
Mass: Unavailable
Orbit: GEO Halo Orbit
Cost Estimate: Unavailable

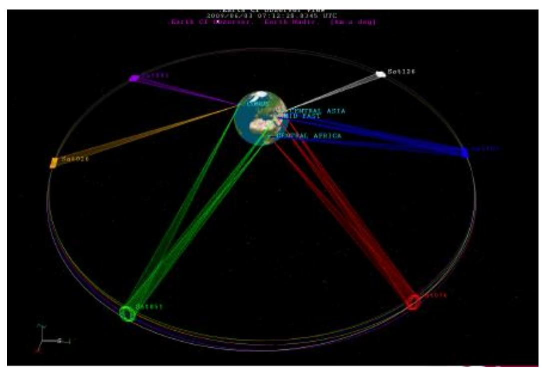
Figure D-12 — Aerospace Corp Military Concept

In the Aerospace Corp military concept (Fig. D-12), each space vehicle can provide 200 kW, but several vehicles would contribute to the same locations. This model would provide a military base with 3 MW to 5 MW. Laser in this context could improve field logistics, and reduce exposure to IEDs for fuel deliveries. The ground receiver size would only be 60 meters in diameter and each laser beam would be a fraction of the Sun's intensity.

Source: Penn, J., Law, G. "Future SSP Systems Concepts: the Laser Option – Commercial and Military Applications." *International Symposium on Solar Energy from Space*. 2009.

EADS Astrium Concept (~2010)

Organization: EADS/Astrium
PB Method: IR Laser
Power Delivered: Unavailable
Mass: Unavailable
Orbit: GEO
Cost Estimate: Unavailable


Figure D-13 — EADS Astrium Concept

The EACS Astrium Concept (Fig. D-13) employs an infrared laser to mitigate concerns of harming people or objects in the event that the laser beam was misdirected for any reason. The company (now Airbus) has tested the IR laser in its labs and seeks to achieve an 80% conversion efficiency. The concept is not near an operational stage.

Source: https://phys.org/news/2010-01-european-space-company-solar-power.html Accessed November 15, 2017.

Solaren SSP (2011)

Organization: Solaren Company
PB Method: MPT via RF transmitters
Power Delivered: 0.25 GW to 2.25 GW
Mass: Unavailable
Orbit: GEO
Cost estimate: $6 billion-$8 billion

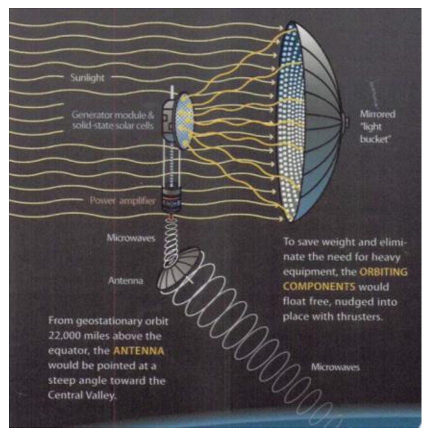

Figure D-14 — Solaren SSP

Solaren bills itself as a viable commercial option for SSP with active investors. They claim extremely mature and efficient conversion technologies with a solid financial plan. Solaren has also been awarded key patents on their design in most major spacefaring countries. The Solaren SSP concept (Fig. D-14) features a free-floating orbital mirror that reflects sunlight onto a PV array. Power conversion then occurs from the PV array to the transmitting antenna. The co-orbiting reflector dish would maintain position with small maneuvering thrusters.

Source: http://www.solarenspace.com/solaren-space-solar/ssp-overview/ Accessed November 15, 2017.

Solar High SSP (2012)

Organization: Solar High Study Group
PB Method: MPT @ 2.45 or 5.8 GHz
Power Delivered: Order of GW
Mass: Unavailable
Orbit: GEO
Cost estimate: Unavailable

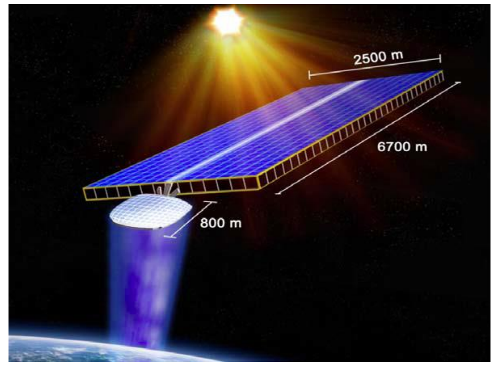

Figure D-15 — Solar High SPS

The Solar High SSP concept (Fig. D-15) is based on an update of the 1970s DOE/NASA reference system. The design itself comprises a large solar collection grid connected to a MPT transmitting antenna. The transmitting antenna would be about 800 meters in diameter, and would be accompanied by a 2.5 x 6.7 kilometer solar collection array. Assembly on orbit and modularity would likely be needed.

Source: Jaffe P, and McSpadden J. “Energy Conversion and Transmission Modules for Space Solar Power.” *Proceedings of the Ieee*, vol. 101, no. 6, 2013, pp. 1424–1437 . doi:10.1109/JPROC.2013.2252591.

Lew Fraas Orbiting Mirrors (2012)

Organization: JX Crystals Inc.
PB Method: Direct reflection
Power Delivered: 75 GW (total all receiving stations)
Mass: 1,600 t per mirror
Orbit: 1,000 km LEO
Cost estimate: $11 billion

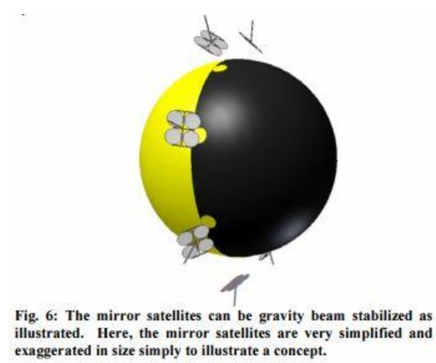

Figure D-16 — Lew Fraas Orbiting Mirrors

The Lew Fraas Orbiting Mirrors concept (Fig. D-16) incorporates a constellation of 18 mirror satellites augmented by 20º latitude in a polar sun-synchronous orbit. Each mirror satellite contains several two-axis tracking mirror segments that directly reflect solar energy down to the surface of the Earth. The orbit was selected to extend the limits of dawn and dusk at the illuminated locations.

Source: Fraas L.M, and 38Th IEEE Photovoltaic Specialists Conference PVSC 2012 38th IEEE Photovoltaic Specialists Conference, PVSC 2012 Austin, TX, USA 2012 06 03 - 2012 06 08. “Mirrors in Space for Low-Cost Terrestrial Solar Electric Power at Night.” *Conference Record of the Ieee Photovoltaic Specialists Conference*, vol. 2862-2867, 2012, pp. 2862–2867. doi:10.1109/PVSC.2012.6318186.

SPS-ALPHA Mark I (2013)

Organization: Artemis Innovation Management Solutions
PB Method: MPT via RF phased array
Power Delivered: 30 kW (second iteration), 2 GW (sixth iteration)
Mass: 12.1 t (second iteration), 34,814 t (sixth iteration)
Orbit: LEO (initial concepts), GEO (final platforms)
Cost estimate: $500/kg target

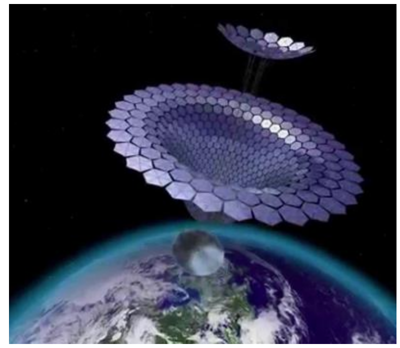
Figure D-17 — SPS-ALPHA Mark I

A goal of the SPS-ALPHA Mark I concept (Fig. D-17) was to increase the TRL level of the design from TRL 1 to TRL 3. The concept is comparatively well-documented. Concept implementation relies on significant paradigm changes in space systems design and assembly. The three main components of the concept include the transmitting antenna, a reflective sunlight interceptor system, and a connecting truss. The concept has plans for Design Reference Missions 0-5, with each subsequent mission having increasing size and power delivery.

Sources:
https://www.nasa.gov/sites/default/files/atoms/files/niac_2011_phasei_mankins_spsalpha_tagged.pdf Accessed 2017-11-16 and Mankins J.C, et al. "SPS-Alpha: The First Practical Solar Power Satellite Via Arbitrarily Large Phased Array (a 2011-2012 NASA N1AC Project)." *Proceedings of the International Astronautical Congress, IAC*, vol. 9, 2012, pp. 6950–6958

GEO Beaming to WPT Relay (2013)

Organization: R.M. Dickinson
WPT Method: Laser from orbit to relay,
MPT @ 2.45 GHz from relay to ground
Power Delivered: 20 MW
Mass: Unavailable
Orbit: GEO and upper atmosphere
Cost Estimate: Unavailable

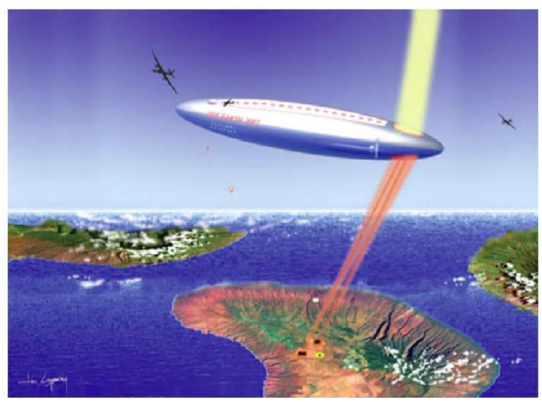
Figure D-18 — GEO Beaming to WPT Relay

With the GEO Beaming to WPT Relay concept (Fig. D-18), a WPT laser would transmit to an airship above 95% of the atmosphere, and the airship would then relay the energy to the ground via MPT. The laser would operate at 1.4 microns so that misalignment would result in large atmospheric absorption. The ground receivers would have circularly polarized elements to accommodate the airship's change in orientation as a function of wind direction. As this concept combines laser and microwave power beaming, it must contend with the conversion inefficiencies of each.

Source: Dickinson R.M. "power in the sky: requirements for microwave wireless power beamers for powering high-altitude platforms." *IEEE Microwave Magazine*,_vol. 14, no. 2, 2013, pp. 36-47., doi: 10.1109/MMM.2012.2234632

Hyland Power Star (2014)

Organization: David Hyland, Texas A&M
PB Method: MPT via "collectennas"
Power Delivered: Unavailable
Mass: Unavailable
Orbit: Unavailable
Cost estimate: Unavailable

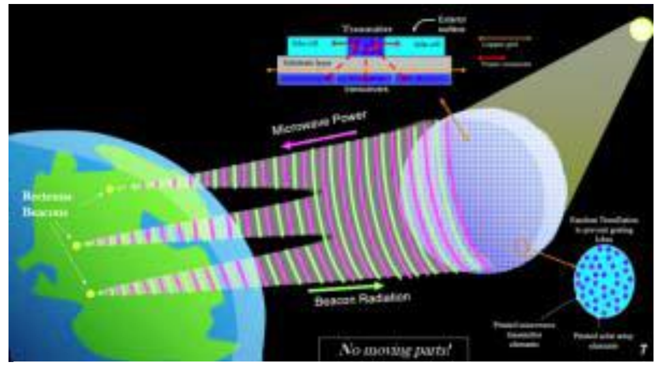

Figure D-19 — Hyland Power Star

In the Hyland Power Start concept (Fig. D-19), solar collectors and microwave transmitters would be printed on a thin fabric and the collectors and antennas are combined into modules called "collectennas." The star would be assembled from oval strips that when attached together form a sphere, much like a beach ball, and would be inflated to 1 km diameter in orbit. Ground beacons would specify the transmitted power distribution. The collectennas would then sense the beacons, amplify them, and transmit back and allows for more than one beam at a time. The star ostensibly requires no aiming or pointing mechanisms, minimizes space assembly, has dynamic stability, and could provide a range of desired field distribution on the ground.

Source: David C. Hyland and Haithem A. Altwaijry, "Power Star: A New Approach to Space Solar Power," 2016, 20 pages.

Multi-Rotary Joints SSP (2015)

Organization: China Academy of Space Technology
PB Method: MPT @ 5.8 GHz
Power Delivered: 1.3 GW
Mass: ~10,000 t
Orbit: GEO
Cost estimate: $30 billion


Figure D-20 — Multi-Rotary Joints SSP

The Multi-Rotary Joints SSP concept (Fig. D-20) features a large space architecture. The transmission dish is 1 km in diameter with an overall vehicle length of close to 12 kilometers. The ground receiving rectenna is sized at 5 kilometers in diameter. A key design feature of this concept allows the solar arrays to rotate about their support truss to track the sun, while providing multiple current paths to the transmitter. It is proposed to launch to LEO on conventional rockets, followed by solar electric propulsion boost to GEO. The target lifetime of the space platform is 30 years.

Source: https://spacejournal.ohio.edu/app/generic.html. Accessed November 16, 2017.

Sunflower Thermal Power Satellite (2015)

Organization: Keith Henson
PB Method: MPT @ 2.45 GHz
Power Delivered: 5 GW
Mass: 29,500 t
Orbit: GEO
Cost estimate: $40 billion-$70 billion

The Sunflower Thermal Power Satellite (Fig. D-21) exhibits a heat engine-based solar power satellite. The concept proposes launch to LEO, and then use of a solar electric tug to boost to GEO. Initial cost estimates for this design including construction labor and transportation are $2,400/kW. The concept is designed to generate 10 GW in space, with 5 GW delivered to the ground receiving array. The concept relies on a 1 km transmitting array and a 10 km ground-receiving array.

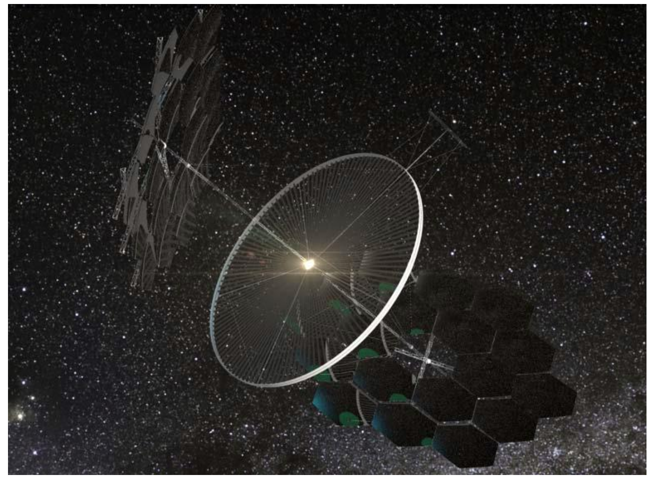

Figure D-21 — Sunflower Thermal Power Satellite

Source: https://spacejournal.ohio.edu/issue18/sunflower.html. Accessed November 15, 2017.

SSPS-OMEGA (2015)

Organization: Xidian University, China
PB Method: MPT @ 5.8 GHz
Power Delivered: 2 GW
Mass: 22,953 t
Orbit: GEO
Cost Estimate: Unavailable

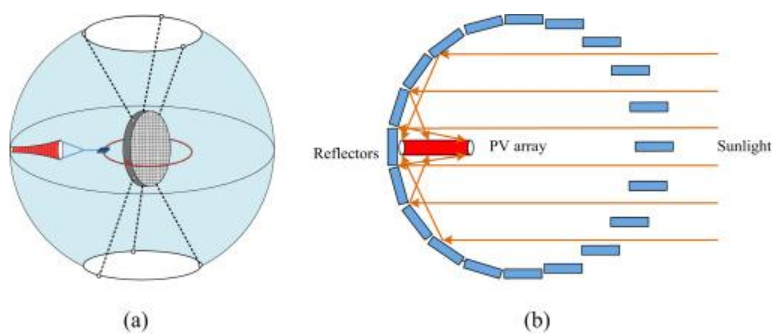

Figure D-22 — SSPS-OMEGA

The SSPS-OMEGA (Fig. D-22) comprises four main components: (1) spherical solar power collector, (2) hyperboloid PV cell array, (3) power management and distribution, (4) microwave transmitting antenna. A spherical shell made of adjustable position reflectors would orbit the Earth. The side of the sphere facing the Sun would rotate its reflectors to permit sunlight to enter the inside of the sphere while the back of the inside would reflect the light onto a PV array. As the sphere orbits, the reflectors are continuously adjusted to permit constant sunlight entrance into the sphere. The space platform scale is a transmitting antenna of approximately 1 kilometer in diameter.

Source: Yang, Yang, et al. "A Novel Design Project for Space Solar Power Station (SSPS-Omega)." *Acta Astronautica*, vol. 121, 2016, pp. 51–58., doi:10.1016/j.actaastro.2015.12.029

Tin Can SPS (2015)

Organization: IUPUI
PB Method: MPT @ 2.45 GHz
Power Delivered: 5.35 GW
Mass: 4,930 t to launch
Orbit: GEO
Cost estimate: $24.4 billion

Figure D-23 — Tin Can SPS

A distinguishing feature of the Tin Can SPS concept (Fig. D-23) is the lack of any moving parts. Due to the cylindrical PV collector, no manipulation of collectors or mirrors is necessary. In addition, the warm sun-facing panels can radiate their heat onto the cool space-facing dark panels. It is envisioned that structural misalignment would result in negligible solar collection losses, and that the transmitter could compensate for misalignment through phase shifting. This concept relies on lunar ISRU fabrication of the PV panels where they can be electromagnetically delivered to the structural framework launched from Earth.

Source: Peter J. Schubert, Sheylla Monteiro Pinto, Bruna C. Pires, Moises do Nascimento, Edward Barks, Jonathan Nderitu, Gabriel Oliveira Goncalves, and Fatih Tokmo. "Analysis of a Novel SPS Configuration Enabled by Lunar ISRU", AIAA SPACE 2015 Conference and Exposition, AIAA SPACE Forum, (AIAA 2015-4648)

Space Solar Power Initiative (2015)

Organization: Caltech–Northrop Grumman
PB Method: MPT
Power Generated: 910 kW per module
Mass: ~400 kg per module
Orbit: GEO
Cost estimate: Unavailable

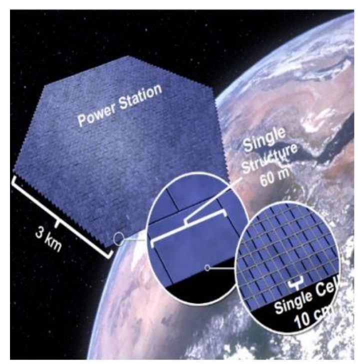

Figure D-24 — Space Solar Power Initiative

The Space Solar Power Initiative concept (Fig. D-24), developed by a collaboration between Caltech and Northrop Grumman, is composed of single units called tiles. One tile contains the PV cell, DC-RF convertor, transmission antenna, timing control, and thermal management. The overall flat structure is a hexagon with 3 km long sides and is composed of 6,500 60m x 60m modules flying in formation. Each module contains 300,000 tiles.

Source:
http://www.mtu.edu/ece/department/faculty/full-time/zekavat/pdfs/ssp-2017/ng-caltechpanel-sspi-technology-maturation-approved.pdf. Accessed 2017-11-28.

SPS-ALPHA Mark II (2016)

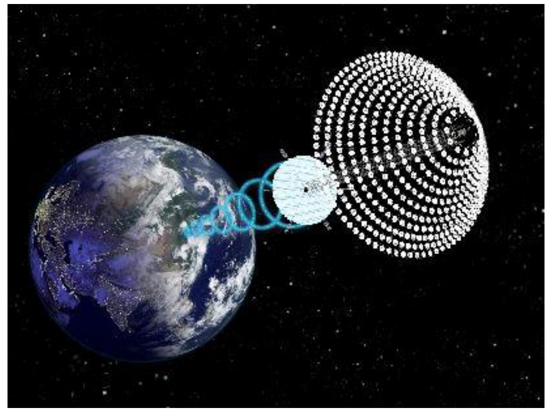

Figure D-25 — SPS-ALPHA Mark II

Organization: Mankins Space Technology, Inc.
PB Method: MPT @ 2.45 GHz
Power Delivered: 2.1 GW
Mass: 10,000 t
Orbit: GEO
Cost estimate: $11 billion

The SPS-ALPHA Mark II (Fig. D-25) is an updated architecture to the one proposed as SPS-ALPHA Mark I. The design focuses on hypermodularity with more than 1,000,000 small modules to create a single enormous satellite. This aims to take advantage of learning curves and economies of scale to reduce manufacturing costs. The transmitting array would be 1.7 kilometers in diameter with a 6 kilometer ground receiving rectenna. Other updated features include revised WPT systems, transportation architectures, and platform sizing.

Mankins, J.C., "New Developments in Space Solar Power." *Proceedings of the International Astronautical Congress, IAC*, 2016.

CASSIOPeiA Solar Power Satellite (2017)

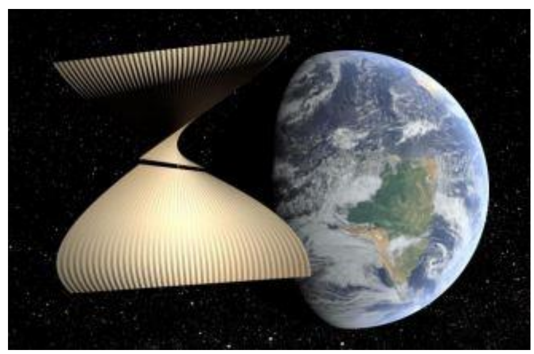

Figure D-26 — CASSIOPeiA Solar Power Satellite

Organization: Ian Cash/SICA Design Limited
PB Method: MPT @ 5.8 GHz
Power Delivered: 430 MW
Mass: 400-900 T
Orbit: GSO
Cost estimate: Unavailable

The CASSIOPeiA Solar Power Satellite (Fig. D-26) concept features a space platform with no moving parts and no cosine losses of solar energy collection. In addition to having PV cells located over its helical shaped structure, RF transmitters are also distributed across the structure. The overall shape and architecture also make this concept potentially suitable for deployment inside stratospheric balloon. Power would be transmitted to the ground via a phased array to a rectenna measuring 3.16 kilometers in diameter.

Source: http://www.mtu.edu/ece/department/faculty/full-time/zekavat/pdfs/ssp-2017/ssp2017-cassiopeia-sica-design-presentation.pdf. Accessed November 28, 2017.

APPENDIX E – FREQUENTLY ASKED QUESTIONS ABOUT SPACE SOLAR

This appendix addresses common questions posed by both laypeople and those with technical backgrounds. The questions address issues relevant to both microwave and laser power beaming. When appropriate, some answers are given for both grid and remote installation contexts. Answers generally pertain to the current state of available technology.

1. *Why should space solar be considered?*

   Answer: Sunlight in space is brighter and generally unimpeded versus sunlight on the Earth, given the lack of weather effects, the atmosphere, and nighttime.

   If the solar energy in space could be effectively collected and transmitted to areas of need on Earth, particularly those without existing grid infrastructure, it could prove valuable.

2. *Is there a danger to people or animals from a microwave power beam?*

   Answer: A system can be designed to operate within accepted safety parameters.

   Some ask whether power beaming would "fry birds." A study published in 1985 examining the effects of microwave power transmission on birds at 2.45 GHz found that at 250 W/m^2, more than twice the IEEE standard and five times the ICNIRP standard for human exposure, there were no discernible differences between the control group and the exposed birds[5].

3. *Is there a danger to people or animals from a laser power beam?*

   Answer: A system can be designed to operate within accepted safety parameters.

   Laser transmission methods may pose a risk of thermal or eye damage, depending on the wavelengths and power densities involved. As a result, there are likely to be safety protocols in place for laser implementations. There is work being conducted on systems at "eye-safer" wavelengths (such as 1500 nm) and on safety interlock systems that would mitigate such hazards [B2]. It is worth noting that portions of the infrared spectrum have safety thresholds that allow ten times as much power as for microwaves.

4. *Would microwave power beaming be dangerous to aircraft and satellites?*

   Answer: This would depend on the operating frequency and power density.

   It is anticipated that exposure for aircraft and satellites would be minimal for power densities within safety limits, with risk further reduced by the short amount of time they are likely to spend in the beam. In general, microwave power transmission would pose little threat to the structural integrity of an aircraft or satellite, regardless of industrial or military application. However, there is potential risk to avionics and other control systems for both types of vehicles. Microwave power beaming for installations with airfields or radars could create interference. Appropriate planning might reduce or eliminate interference threats, though the risks associated with harmonics, side lobes, phase stability, and thermal noise could be considerable.

5. *Would laser power beaming be dangerous to aircraft and satellites?*

   Answer: Existing precedents show that laser power transmission could be implemented with negligible risk to aircraft and satellites.

[5] F. E. Wasserman, T. Lloyd-Evans, S. P. Battista, D. Byman and T. H. Kunz, "The Effect of Microwave Radiation (2.45 GHz CW) on the Molt of Housefinches (Carpodacus Mexicanus)," Space Solar Power Review, vol. 5, pp. 261-270, 1985.

As lasers operate within the optical spectrum, the major concerns of interfering with electronics and guidance systems are not a concern for lasers. If a safety interlock or deconfliction system used by the Laser Clearinghouse for a laser power beaming system failed to turn off the beam in the event of aircraft or spacecraft impingement, the amount of energy absorbed would still be comparatively small because of the high rate of speed and the resulting short exposure time.

6. *Won't the multiple conversions and the enormous cost to implement space solar negate any benefit of the greater access to sunlight in space and the prospect of global distribution?*
   Answer: Possibly, but efficiencies for relevant devices for both microwave and laser conversion are increasing.

   Focus often naturally falls on conversion efficiency, but it is an aspect of a perhaps more important metric for determining economic feasibility: specific power, measured in watts per kilogram. If a space segment can be implemented with a very high specific power, it may be able to close the financial case. This is because even if it is not especially efficient, it will require less mass to be put in space, and thus decrease the cost of power.

7. *How much area does the receiver site take up?*
   Answer: The size of a ground receiver can vary widely based on the architecture implemented, the power density at the receiving site, and required energy for the site.

   A receiver might be scaled to the power needed. For a remote installation application with high transmitted power densities, the area can be smaller. To remain within existing safety limits, incident power densities for microwave would not exceed 100 W/m^2, and for laser would not exceed 1,000 W/m^2. The effective utilizable power density of the receiver would be lower in accordance with the receiver conversion efficiencies. Systems exceeding existing power density thresholds could be higher.

8. *Could solar panels double as laser power receivers?*
   Answer: This is a possibility, but currently deployed solar panels may not be a good match to the laser wavelengths that might be used, and laser light might be of a different power density or be less uniform than sunlight, which could cause thermal problems.

9. *How is the power beam controlled?*
   Answer: There are several demonstrated techniques for effective beam control.

   To steer the beam, a technique called retrodirective control may be used. An encoded signal is sent from the receiver to tell the satellite how to steer the energy. One example of retrodirective control was in 2008 by Kaya and Mankins[6]. In this experiment, the group accomplished successful pointing of a microwave beam over a distance of 148 km from a Maui-based array to the main island of Hawaii. Although the actual power received was an infinitesimal amount of what was transmitted, the experiment showed that power could be accurately pointed over large distances.

10. *Will the atmosphere interfere with power transmission?*
    Answer: It depends on the wavelength used, and possibly the weather conditions.

    Microwave power transmission at 2.45 GHz and 5.8 GHz would avoid much of the attenuation by the atmosphere, and any potential weather. The shorter wavelengths considered for space

[6] https://www.wired.com/2008/09/visionary-beams/

solar (35 GHz, 94 GHz, and optical wavelengths) could incur significant attenuation due to the weather, but clear air attenuation by the atmosphere would be fairly low.

11. *Can a solar power satellite system be used as a weapon?*
    Answer: This is unlikely, but would depend on the specifics of the system.

    Space solar systems can be designed to transmit only to the intended ground receivers, and could be limited by design to safe ground power densities. The larges powers and apertures needed for a weaponized system would generally distinguish it from and energy transmission system.

12. *Could a space solar system be serviced in orbit?*
    Answer: Yes, if current efforts for satellite servicing are any indication of future capabilities.

    Space solar systems would likely be highly modular, making servicing and possible replacement of components more straightforward. Some advanced systems might be capable of self-repair.

13. *Will solar power satellites be vulnerable to solar activity like solar flares and coronal mass ejections?*
    Answer: Possibly. Methods of protecting satellites for solar activity exist and have shown to be reasonably effective, but not on the scale solar power satellites would require.

14. *What would be the effect of power beams from space solar on astronomy?*
    Answer: Depending on the implementation, it could have a significant impact.

    Because radio astronomy often relies on being able to collect very weak signals, there is a possibility that a power beam from space solar would introduce interference that would make this difficult or impossible at some frequencies. For laser transmission, the effects are likely to be of lesser concern because of the higher directivity of the power beam. The probable effects of a given system would need to be carefully assessed and weighed against the benefits. Because of the sheer size of many proposed solar power satellites, there might also be effects for other areas of astronomy from their thermal and visual signatures.

15. *Does Earth's shadow affect solar power satellites' ability to collect solar energy?*
    Answer: Possibly. The effect becomes diminishingly small for higher orbits.

    For a space solar system in GEO, a satellite would only be in Earth's shadow near the spring and fall equinoxes around local midnight. Over the duration of both equinoxes, an SSP system would be shadowed for 51 hours of 8766 hours per year or only 0.6% of the time. If two satellites are used and are above different points on Earth, one may be sunlit when the other is not, allowing for constant power delivery.

16. *Do increasing PV efficiencies help or hurt the case for SSP?*
    Answer: If the power-beaming link must be held to accepted safety limits, increasing photovoltaic efficiency may hurt the case for space solar. This is because the power density for terrestrial solar could increase, but space solar would be held to an arbitrary ceiling. However, implementations that do not depend on creating high power densities on the ground might be unaffected.

17. *If we magically had an operational solar power satellite in orbit, could we turn it on?*
    Answer: The spectrum for operation of a microwave power beam has not been allocated, so microwave transmission would likely not be permitted. A laser solar power satellite, on the other hand, might be immediately usable if it met certain criteria.

18. *Is it possible that it will never make sense to build solar power satellites?*
    Answer: Yes. Solar, fusion, advanced fission, space industrialization, high-density storage, stabilized or displaced demand, all might make it possible that space solar would not be feasible or desirable, depending on the context and externalities.

APPENDIX F – SELECTED TECHNOLOGIES INHERENT IN SPACE SOLAR

Solar Energy Collection and Management

The central functionality associated with solar energy collection is the conversion of incoming sunlight into a form suitable for subsequent transmission to Earth. A secondary solar energy collection technology that may be important is that of large, thin-film reflector systems.

Photovoltaic Cells

Photovoltaic (PV) cell and array technologies have advanced dramatically for terrestrial and space missions and markets during the past 30 years, although in a number of instances the advances that have occurred for terrestrial markets, such as inexpensive but relatively low efficiency PV arrays, are not as useful for in-space applications where secondary systems like structures are expensive to deploy.

Heat Engines

Heat engines come in a variety of types based on the specific thermodynamic cycle that is embodied in the engine, including Stirling engines, Rankine cycle engines, and Brayton cycle engines. Heat engines have the virtue of being simple, closed thermodynamic systems that can convert concentrated solar energy into mechanical movement through a generator into electricity.

Sun-Pumped Lasers

Solar-pumped lasers are a straightforward and elegant idea: incoming sunlight across a broad section of the visible and near visible spectrum is collected and concentrated onto a lasing medium and single spectrum, coherent laser light emerges. This reduces to a single step (a) solar energy conversion, (b) power management and distribution and (c) power beaming.

Power Management and Distribution

The requirements for power management and distribution (PMAD) vary dramatically from one solar power satellite concept and another, as do the variety of PMAD technology options that may be chosen. Generally speaking, the options involve:

- relatively simple and local PMAD at low voltages (e.g., 28 Volts) and direct current (DC)
- relatively complex long-distance PMAD at intermediate to high voltages (1 kV to 5 kV), with the additional requirement that the PMAD system may require the integration of local inverters (to convert DC to alternating current (AC) and/or AC to DC)
- complex long-distance and locally “smart” PMAD capable of reconfiguring inputs/outputs dynamically
- incorporation of either very high voltages (>10 kV) or advanced materials and additional subsystems, such as superconductors with cryogenic cooling systems

Power Beaming

Modalities for Power Beaming

There are three primary ranges of electromagnetic transmissions that have been considered for application in power beaming systems: microwave, millimeter wave, and near visible. There are a variety of systems-level tradeoffs between these wavelengths.

Longer wavelengths, particularly those below 10 GHz, have the advantage of having little attenuation in rain or clear air, and the prevalence of comparatively efficient transmit and receive hardware. Attenuation from both of these causes becomes worse with increasing frequency. However, there are atmospheric windows through clear air at 35 GHz and 94 GHz. There are no windows at higher microwave frequencies for rain attenuation. Another advantage of longer wavelengths is that the technology is mature; inexpensive, highly efficient components are available; but for a given antenna or transmitting aperture diameter, beam divergence is proportional to wavelength. Longer wavelengths therefore, drive the system to very large sizes, more amenable to commercial grid power, but less amenable to levels of a few MW to a few tens of MW that might be appropriate for remote installations. Shorter wavelengths may thus be more appropriate for the latter.

In addition, longer wavelengths, and increasingly, wavelengths of order of a centimeter, must compete for electromagnetic spectrum for communications and must avoid creating interference. Obtaining these frequencies for WPT from the FCC, NTIA, and ITU may be challenging. It is also possible that microwave or millimeter wave frequencies where the atmospheric attenuation is relatively high, may be preferable. This could occur in an RF-rich environment where shielding from the tail and side-lobes of the beam by the atmosphere around the rectenna, may be desired. The resulting loss in power, or the larger satellite needed to supply a given amount of power, may be a price worth paying to supply power to a FOB, though this may not pay for a commercial SPS. Laser (infrared or visible) allows for relatively compact system sizes, but is subject to attenuation by clouds. In addition, components are less efficient. There may also be a concern regarding treaties about lasers in space and a perception of weaponization.

State of the Art in Beaming Device Technologies

There a number of technological choices for power beaming; these options fall broadly into a range of wavelength choices, including both RF and laser light options, described below.

Microwave to mm-Wave Wavelengths, comprising several distinct technologies, including the RF power generator device, power-processing electronics operating in conjunction with the power device, and the RF antenna. Key technologies include Solid State Power Amplifiers (SSPAs) and vacuum electronics.

Near-visible Wavelengths, comprising a number of technologies including the laser light source, the optical beam expander and the pointing system. Key technologies include diode and fiber lasers.

For both microwave and laser sources, more detail can be found in a previous report[7].

Receiver Technologies

The ground receiver for Space Solar power beaming is essentially an array, incorporating the technologies appropriate for the particular EM frequency being employed. However, the details will vary significantly depending on the wavelength to be used.

(1) *Microwave Power Beaming* - In the case of microwave technologies, this technology is rectifying antenna or "Rectenna," first invented in the 1960s and capable of high RF-to-DC conversion efficiency. In the mid-1970s, a rectenna was demonstrated at a frequency of 2.45 GHz with an efficiency that exceeded 90% (RF to DC). Additional technology requirements for a microwave power beaming system receiver include the transmitter of a "reference signal" for use by retro-

[7] https://apps.dtic.mil/docs/citations/ADA513123

directive phase control at the platform transmitter array. A depiction of a rectenna array appears in Figure F-1.

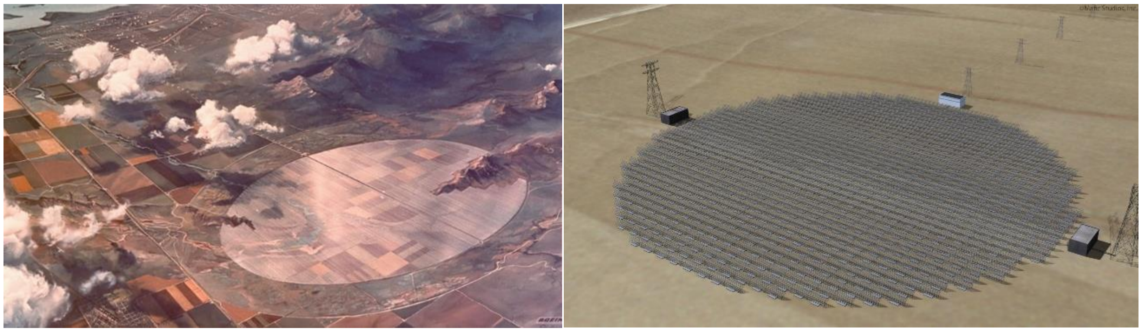

Figure F-1 – a rectenna receiving array as depicted in (a) the NASA/DOE space solar studies, and (b) a more recent depiction courtesy and © Mafic Studios, Inc.

(2) *Millimeter-wave Power Beaming* **-** In the case of millimeter-wave technologies, the receiver may also be a rectenna, although at these frequencies, the scale of the individual antenna elements will be small (typically less than 1 cm). Expected efficiencies for such systems will be a function of the specific frequency, but are expected to be less than microwave rectennas or laser-tuned PV array receivers.

(3) *Laser Power Beaming* **-** In the case of laser power transmission at visible or near-visible wavelengths (roughly 1 micron), the receiver technology of choice is a frequency tailored PV array. In this case, efficiencies on the order of 70% (laser to DC) might be expected. This array would be physically oriented to face the transmitter but might otherwise resemble a conventional PV array, including conventional interfaces to the local power systems. To achieve higher conversion efficiencies, a local concentrator PV (CPV) cell approach could be used, although this would necessitate regular cleaning of the concentrator refraction optics, and precision pointing of the CPV array.

Space System Implementation

Overview

A variety of key, although secondary space systems technologies, are needed for the implementation of space solar, including (1) access to space, (2) in-space assembly and construction, and (3) structures, materials, and related technologies.

Space Access

There are two primary and closely related areas of space access systems and technologies: Earth-to-orbit (ETO) transportation and in-space transportation.

(1) *ETO Transport* **-** For low Earth orbit (LEO) options, whether to inclinations that are nearer to equatorial or to polar, the ETO system (launch vehicle and any expendable upper stage) provides essentially all of the transportation needed for SPS deployment. For modular SPS options, a very wide range of launchers could be used to ETO transport. Newer launchers, such as those being developed by the companies SpaceX and Blue Origin should be capable of launching the modular parts of either microwave or laser power beaming platforms to LEO, either for deployment there or for subsequent transport to a higher operational orbit such as GEO.

(2) *In-Space Transport* - For GEO and similar location options, advanced technology in-space transportation systems/technologies are crucial to the economical deployment of SPS. Using low fuel efficiency (low "specific Impulse" or "Isp") propulsion systems, the cost of in-space transportation will be 3-10 times greater than with high Isp options such as solar electric propulsion (SEP) systems. These supporting technologies (for example, in the class of a 50 kW SEP system) have been developed to a high level of maturity for NASA's asteroid return mission (ARM) during the past several years, although these have not yet been demonstrated in space.

In-Space Assembly

All SPS concepts involve some version of in-space assembly, and all benefit from the advances in robotic technology that have been made since the very early studies of Space Solar in the 1970s. However, the specific requirements and details of in-space assembly technology requirements, like power management and distribution, depends entirely upon the SPS concept involved. There are three primary types of in-space assembly that are relevant to space solar during the coming 10-20 years: (1) "stick-build" type robotic assembly at a pre-positioned assembly and construction facility in space, in the manner of an "erector set"; (2) robotic assembly of specifically designed modular elements, in the manner of Legos or Tinker-toys; (3) kinematically-deployed structural systems, in the manner of a spring-loaded umbrella unfolding; and possibly (4) advanced and additive manufacturing, in the manner of a 3D printer.

These will typically incorporate individual spacecraft that are launched separately and that subsequently rendezvous and dock to form a larger platform.

Space Structures Considerations

Cost-effective implementation of space solar for remote installations would require the deployment of exceptionally large and low mass structural systems. There are three primary areas: (1) structural systems; (2) structural materials; and (3) dynamics and controls.

Structural Systems

Although they could be implemented at extraordinary cost, using conventional structural systems like those employed for International Space Station, cost-effective SPS would likely entail a range of novel, modular structural systems. These structural systems should enable the reliable assembly of large systems by robotic or tele-robotic means. High aspect ratio, low-mass deployable beams are a technology of potential interest. Various versions of this type have been used for many years in space systems, such as for the deployment of sensitive instruments away from the main body of a science spacecraft, but much larger systems would be required for SPS.

Structural Materials

Accomplishing any existing architecture for future cost-effective SPS will entail the application of materials already in use and new materials now in the laboratory, but ready for application where needed. Although SPS could be implemented with entirely conventional materials such as aluminum alloys, novel materials like carbon nanotubes or nanostructured systems such as metallic foams might be employed.

Dynamics and Controls

For the large, low-mass per unit length and unit area structural systems required for SPS, there would be significant inherent flexibility. As a result, these very large systems will continue to be flexible regardless of the materials used. Consequently, computer modeling of the dynamic behavior of these structures will be a key technology requirement. In addition, the use of appropriate control systems will likely be required; for example, passive or active vibration dampers in combination with distributed sensors at selected locations on the structure.

Ground Integration and Storage

The integration of space solar with power-consuming systems on the ground might resemble that of a ground-based solar power system. Ground integrated systems technologies will include a local receiver, modules to integrate power from the receiver into the local grid, likely including a local inverter to convert received DC to distributed AC, and a local energy storage system.

Space solar architectures almost inevitably involve, to a varying degree, shadowing of an individual satellite and the possibility of unscheduled but short duration interruptions in power beaming, such as the few moments during passage of a satellite in LEO when the beam may need to be suspended. Consequently, many proposed architectures involve either an alternative source of power like a gas turbine generator or an energy storage system, sized for the maximum expected interruption, plus calculated margin. A backup SPS could also be provided. Energy storage onboard the SPS could also be considered to deal with scheduled shadowing by Earth, but this approach would not relieve the requirement for a ground system to deal with beaming interruptions, and it is very likely to be much more expensive than placing a modest energy storage system at the receiver because of the extra mass required.

APPENDIX G – BASING CLASSIFICATIONS, EXAMPLES, AND REGIONS
Forward Operating Bases Classifications

Table G-1– Categories of Forward Operating Bases (FOBs) as Outlined in the Report by SERDP

	FOB tactical base	FOB tactical base	FOB main operations base	Enduring main operations base
Description	Small, platoon-sized FOB designed for tactical operations and co-location within population centers. Provides secure location with only enough logistics capacity to support the camp.	Company or battalion-sized FOB designed for larger tactical operations or missions with a longer duration. Provides secure location with only enough logistics capacity to support the camp.	Regiment or brigade-sized FOB functioning as a main operations base. Has sufficiently robust infrastructure to support a wide variety of missions and can include service member support facilities. Military training, civil affairs missions, and even the capacity to support civilian political functions and NGO activities may be included.	Division-sized FOB functioning as an enduring, semi-permanent main operations base. Has relatively sophisticated infrastructure capable of supporting sustained operations.
Size (# of troops supported)	50	500	1,500	10,000
Footprint	2 acres	16 acres	51 acres	350 acres
Location	Austere - Limited host-nation infrastructure - Example: Afghanistan	Austere- Limited host-nation infrastructure - Example: Afghanistan	Sophisticated- Some host-nation infrastructure - Example: Iraq	Sophisticated- Some host-nation infrastructure - Example: Iraq
Mission duration	Organic - Less than 90 days	Initial - Less than 6 months	Temporary - Less than 2 years	Enduring (Semi-Permanent) - Less than 10 years
Power demand (peak, assumes 1k W/PAX)	50 kW or less	500 kW	1.5 MW	10 MW
Source of power	Limited need for electricity, use of unit tactical generators whenever needed; batteries	Distributed generation. Tactical military generators, commercial generators, up to Army Prime Power	Larger generators, both commercial and military. Consolidation of generators to form centralized power plants. Limited use of host-nation electric grid	Centralized commercial power plants and use of host-nation electric grid

Figure G-1 – Basing classifications – analysis of fuel, water, and waste reductions in base camps

Publically Available Base Layout Examples

Figure G-2 – The "Q-West" installation in Iraq with notional 1 km and 500 m diameter space solar receivers.

Figure G-3 – Bagram Airbase in Afghanistan with a notional 1 km and 500 m diameter space solar receivers.

Figure G-4 - Camp Lemonnier in Djibouti, with a notional 500 m diameter space solar receiver and a collection of several 50 m diameter receivers providing equivalent power (shown between runways).

Figure G-5 - Camp Arifjan in Kuwait shown with a notional 500 m diameter space solar receiver and clusters of 50 m diameter receivers.

Figure G-6 - The former Korengal Outpost in Afghanistan, shown with notional 50 m and 11 m diameter space solar receivers.

Additional Details for Design Reference Regions

(1) *A low-latitude Pacific island* located between 20°N and 20°S latitude characterized by islands in the South China Sea, and around Indonesia, New Guinea, Micronesia, Melanesia, and Polynesia. They were chosen because they are isolated in terms of distance, and thus have relatively minimal proximate military threat exposure. They are, however, susceptible to tropical cyclones, significant rainfall, seismic events, and naval blockades or the threat of such. The elevation of a typical FOB in this region is typically less than 100 m above mean sea level (MSL) and they are characteristically extremely humid all year round, with around 3050 mm of annual rainfall and a mean temperature of 26.5 °C. This means that they are in a biologically active zone where plant growth could create problems for ground equipment and structures such as a large receiver array. Several of the islands also feature active volcanoes with Tinakula and Kavachi being the most active. The Solomon Islands, located between latitudes 5° and 13° South and longitudes 155° and 169° East were used as a specific location for modeling. It is not an area of particular interest today, but the U.S. military has an extensive history of operations in this area. The Solomons consist of a large number of islands including Chioseul, Shortland Islands, New Georgia Islands, Santa Isabel, Russel Islands, Nggela, Malaita, Guadalcanal, Sikaiana, Maramasike, Ulawa, Makira, Santa Ana, Rennel and Bellona, Santa Cruz Islands and several additional small islands. Most of these islands can be accessed

by ships, while some islands feature advanced facilities and airfields. The biggest SSP challenges are related to transmitting power through heavy precipitation and dealing with an aggressive biosphere.

(2) *A Mid-latitude island* located above 20°N and below 20°S latitude, which includes the Hawaiian Islands, all of the Mediterranean, Formosa, parts of the Caribbean, and the islands of the Indian Ocean. These islands are less vulnerable to seismic activity, but have a history of massive typhoons. Some are politically unstable and vulnerable to the threat of naval blockade. The physical security of most of the installations in these regions is not a major concern, but large indigenous populations could become a threat in civil emergencies. The Greek Aegean island of Santorini, in the Cyclades archipelago is used as a model for design purposes. Its coordinates are 36°25'N 25°26'E, and the maximum elevation is 567 m, which could result in terrain masking since most of the usable land is below 200 m MSL. These islands generally have warm summers and temperate winters with temperatures ranging from 26 °C to 12 °C. At Santorini, there is not much rain and there are no rivers. This creates a water supply problem, whereas many of the other islands in this group have abundant rainfall. The biggest ecological and geological challenges are earthquakes and volcanism.

(3) *A mountainous desert* located between the Equator and 35°N. This picks up the mountains of Afghanistan, where we have a significant number of installations located today, and Pakistan and Eastern Turkey. The area is characterized by significant political and military threats, the need for protected perimeters, and by generally being landlocked, making resupply difficult and expensive. This is further complicated by the extensive use of improvised explosive devices and hostile insurgencies. Climate change may increase the prospect of desertification and sandstorm frequency. The area is also geologically unstable with numerous earthquakes that pose both an immediate threat and can create civil crises. For DRR purposes, the central region of Afghanistan at 33°N and 65°E is used as a specific design reference location. Typical elevations are between 1500 m and 3000 m, which may create terrain-masking issues. There is little rainfall, further complicating the resupply problem since water competes with fuel for logistics accommodations. The temperature range is extreme, with a range of -20 °C to 50 °C. This imposes significant seasonal variability in energy needs.

(4) *A subtropical desert* located between 10°N and 35°N. This picks up Northern African, Ethiopia, Somalia, and a significant number of the Gulf States. These locations are also vulnerable to political and military unrest, but are generally accessible by sea for resupply. Mogadishu, Somalia located at 02°02'N by 45°21'E is used as a model for analysis. The temperature range is consistent with its proximity to the Earth's equator: in the 30°C-40°C range, while the land is arid. There are occasional monsoon conditions along the long Indian Ocean coastline. The mean elevation is above 410 m above MSL with the highest point being Mount Shimbiris at 2416 m; however, Mogadishu itself has a nominal elevation of 10 m.

(5) *A tropical jungle* located between the Equator and 15°N, which picks up all of Indochina, sub-Saharan Africa, Central America, and the northern tier of South American countries. Because these areas extend significant distances inland and are generally underdeveloped in terms of transportation infrastructure, resupply is difficult, dangerous, and expensive. An undeveloped site in Guaviare, Colombia is used as an exemplar location. Its nominal coordinates are 2°N by 72°W. The area has been the site of the Colombian conflict that began in the 1960s between the Colombian government, crime cartels, and left-wing guerrilla organizations like the Revolutionary Armed Forces of Colombia, and the National Liberation Army. The mean elevation is around 200m and temperatures range between 24 and 38 °C with a wet and dry season. The region is also biologically active.

(6) *A polar site* located above 60°N, covering artic sea lanes and involving potentially both land and sea-based FOBs. Physical security of the bases is not currently a concern, since these areas are sovereign U.S. or Canadian territories. The biggest challenges in the polar region are the extreme seasonal variations in the load cycle and the high latitude issues for GEO satellite coverage. The Seward Peninsula at 66°24'N by 164°38'W was chosen because of its exposed location and high latitude. The highest point in the region is Mount Osborn at 1,437 m, but the site was located near the coast below an elevation of 100 m. Temperature variations are extreme—significantly subzero in the winter with extended periods of minimal sun. A polar site might resemble in some fashion the McMurdo Station in Antarctica, as pictured in Figure ; note the predominance of the fuel depot. Access to the sea is important for resupply.

Figure G-7 - Antarctica's McMurdo Station, as photographed by Gaelen Marsden in 2006.

An urban wasteland was defined to study a particularly difficult military environment. For study purposes, urban areas were assumed to be near 30°N latitude and several hundred kilometers from a seaport. These installations exist in the midst of a severely compromised infrastructure with enemy/hostile combatants operating at very close range out of the rubble of the city. The operational perimeter is the outer barrier of the fortified compound. Aleppo, Syria at 36°13'N by 37°10'E was chosen as an example. It is located approximately 380 m MSL with a cool steppe climate with average high and low temperatures of 23.8 °C and 11.1 °C, respectively. Average precipitation is about 330 mm/year.

APPENDIX H – LESSONS FROM PRIOR LARGE SYSTEMS AND TECHNOLOGY DEVELOPMENT HISTORY

Lessons from previously developed large or complex systems and technology may offer guidance for the challenges inherent in space solar. As cost is a major factor, it is worth noting that in the development phase, the resulting capabilities are generally not competitive on cost. Indeed, it may take decades for systems to mature to the point of cost-competitiveness. Other systems may have been less affected by cost, but still presented long development timelines.

Space projects like communication satellites, the International Space Station, and the Global Positioning System each took many years of development prior to coming to fruition, and of those, only communication satellites are profitable today. Even within the communication satellite sector, monumental financial failures can be found, such as Motorola's loss of billions of dollars with the Iridium system, traceable in part to stiff competition and falling costs from terrestrial cellular systems. Space solar may face similar challenges as ground solar and storage become ever cheaper and prevalent.

Energy efforts like the International Thermonuclear Experimental Reactor and the Three Gorges Dam consumed many billions of dollars, evidencing the enormous capital costs for advanced energy technology development and mature technology system implementation, respectively. Infrastructure projects like the Panama Canal, Transcontinental Railroad, and undersea cables faced onslaughts of anticipated and unexpected setbacks prior to their completion.

Energy transitions, such as wood to coal, and coal to oil, have often taken generations. In each case, political will and the courage to be a first mover variously resulted in benefits or losses. Renewable energy technologies like terrestrial solar and wind took decades to approach economic competitiveness with fossil fuels for utility grid applications. Space solar could share commonalities with many of these prior large system and technology developments, but it is critical to recognize the fungible nature of energy and the wide range of other potentially compelling energy alternatives that might render space solar moot or otherwise unattractive.

APPENDIX I – SPACE TRANSPORTATION COST ASSUMPTIONS

The space transportation segment is a major technological and economic challenge for space solar. This appendix establishes a baseline for capability and cost based on current systems, and explores what is needed.

SpaceX advertises the Falcon 9 to be a two-stage rocket capable of placing 22.8 t into LEO and 8.3 t into GTO in the "fully expendable vehicle" configuration[8]. The company's website does not explicitly link the price of a Falcon 9 to the expendable or reusable configuration, but states a price of $62M for 5.5 t to GTO based on the "standard payment plan" configuration, which appears to imply reusability, despite media reports otherwise [https://spacenews.com/spacexs-new-price-chart-illustrates-performance-cost-of-reusability/]. The ratio of mass to LEO vs. mass to GTO is nominally 2.75:1 which implies 15 t could be placed in LEO using the reusable Falcon 9, if the ratio scales linearly for higher orbits. Depending on the assumptions, the current price for a LEO Falcon 9 ride to LEO is slightly over $4,100/kg (~$62M/15 t) assuming the first stage is reusable. Though SpaceX's Gwynne Shotwell has suggested that SpaceX might be able to reduce prices in the future, they have remained steady even as reusability has been demonstrated[9]. Using $62M/launch and a notional future 30% discount, the price to GTO under the "standard payment plan" is ($62M / 5.5 t) x 70% ≈ $7,900/kg.

The SpaceX Falcon Heavy was launched successfully on its first attempt in February 2018[10]. The Falcon Heavy is advertised as capable of placing 63.8 t into LEO and 26.7 t into GTO in the "fully expendable" configuration. The price presented for a Falcon Heavy under the "standard payment plan" is $90M for up to 8 t to GTO. Using a 2.4:1 LEO:GTO ratio (63.8 t/26.7 t) for the Falcon Heavy, the LEO payload for the reusable configuration is around 19 t, which implies a price of just over $4,700/kg ($90M/19 t) to LEO.

For this analysis, 20 t to a 28.5° inclination LEO orbit will be used for the Falcon Heavy performance and the cost/kg will be assumed to be $3,000/kg or $60M for a Falcon Heavy launch to LEO.

It is noteworthy that the current Falcon 9 and Falcon Heavy prices are close to the same per kg for "standard payment plan" launches to GTO ($62M/5.5 t vs. $90M/8 t) – approximately $11,000/kg. SpaceX CEO Elon Musk included in his prepared remarks at a 2004 Senate hearing the assessment that the equivalent of $1,100/kg or less is "very achievable."[11] The $1,100/kg number is about a factor of three less than the assumed pricing and might be achievable within the next ten years if high launch rates are sustained and reusability proves to be fiscally and technically viable.

A 28.5° inclination LEO orbit is not the final orbit for most proposed operational solar power satellite systems. For the purpose of this study, it is assumed that the lowest cost/kg transfer to GEO is achieved by a very high specific impulse (I_{sp}) (~3500 sec) electric/ion transfer stage. Such a stage does not exist today, but predecessors exist for establishing the cost basis.

Getting from LEO to GEO requires around 4.3 km/sec of change in velocity (Δv). Launch from the surface of the Earth to LEO requires approximately 9 km/s due to gravity, drag losses, and the need to achieve orbital velocity. Assuming a nominal 20 t combined payload and transfer stage module in LEO (space solar payload and upper stage), and a notional 3500 second I_{sp} electric/ion propulsion places almost 18 t to GEO. Exploration of electric propulsion for space solar applications can be found in [12], and

[8] http://www.spacex.com/about/capabilities
[9] https://spacenews.com/dont-expect-deep-discounts-on-preflown-spacex-boosters/
[10] https://www.theguardian.com/science/2018/feb/06/falcon-heavy-spacex-rocket-florida-launch
[11] http://www.spaceref.com/news/viewsr.html?pid=12774
[12] https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19990116847.pdf

a depiction of different propulsion options spanning a range of thrust and I_{sp} performance can be found in Figure I-1.

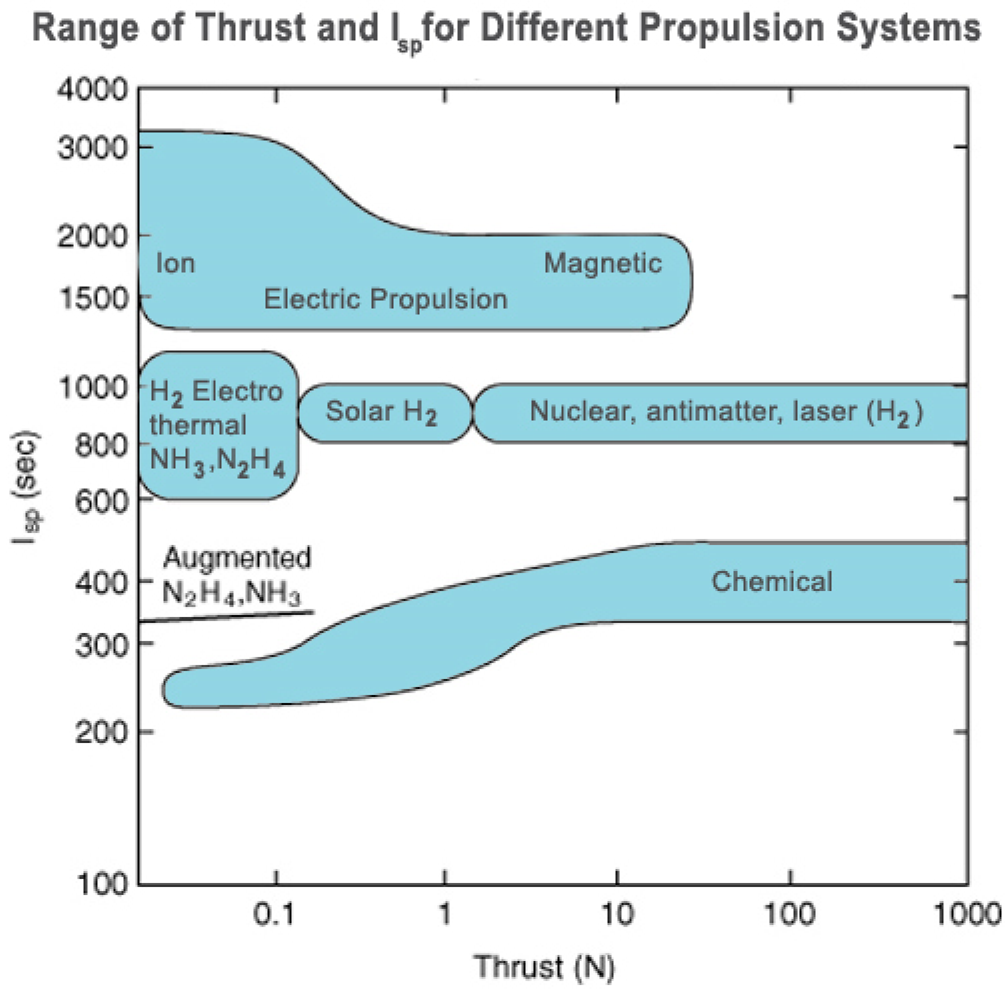

Figure I-1 – Thrust and Isp for different means of propulsions[13]. Note that Nasa Evolutionary Xenon Thruster (NEXT) Xenon ion thruster has demonstrated an I_{sp} in excess of 4000 seconds, outside the range shown in this graphic[14].

The costs associated with the orbital transfer using a notional transfer stage are unknown, but might be characterized to the first order by scaling the $/kg to LEO by the proportion of the Δv from Earth to LEO and LEO to GEO: 4.3 km/s / 9 km/s ≈ 0.5. Scaling the $3,000/kg accordingly gives $4,500/kg to the destination orbit. This assumes the costs of any propellant mass needed for orbital adjustments or station keeping is accounted for elsewhere.

[13] https://insights.globalspec.com/article/10010/ion-thrusters-ultra-efficient-high-speed-spacecraft-propulsion
[14] https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080047732.pdf

APPENDIX J – METRIC TRENDS

The identified metrics of interest can be trended over time, to an extent. This appendix contains instances of such trending, and discusses the limits of existing data.

Space Transportation Cost ($/kg) - The metric that has received the most historical attention when assessing space solar is launch cost. Jones has plotted launch cost to LEO over time[15], as shown in Figure J-1.

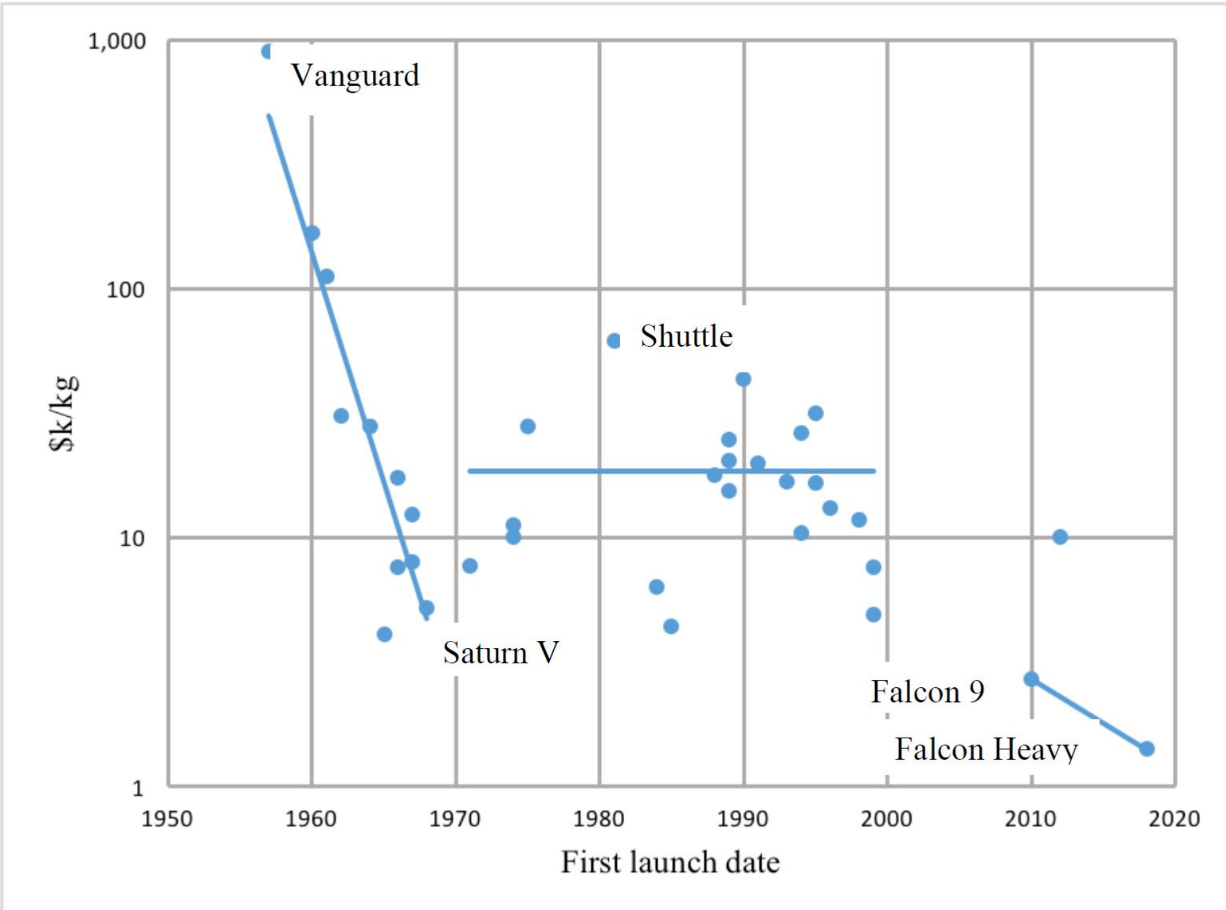

Figure J-1 - Jones' plot of launch costs to LEO over time.

Since LEO is likely not a good orbit for a solar power satellite system, this is only part of the contribution to space transportation cost. Additional cost will be incurred in getting to the target orbit, whether GEO or MEO. This might increase the cost by approximately a factor of 2 or 3, depending on assumptions. As the means of transfer from LEO to the target orbit may vary by implementation, it is more challenging to do a meaningful comparison.

Space Hardware Cost ($/kg) – The majority of satellite operators and manufacturers do not go to great lengths to publicize their costs and system technical information. The information used for plotting this

[15] H. W. Jones, "The Recent Large Reduction in Space Launch Cost," in Proceedings of the 48th International Conference on Environmental Systems ICES-2018-81, 8-12 July 2018, Albuquerque, New Mexico, 2018.

metric in Figure J-2 comes from articles appearing in the space industry media and other sources, and should not be considered as inerrant.

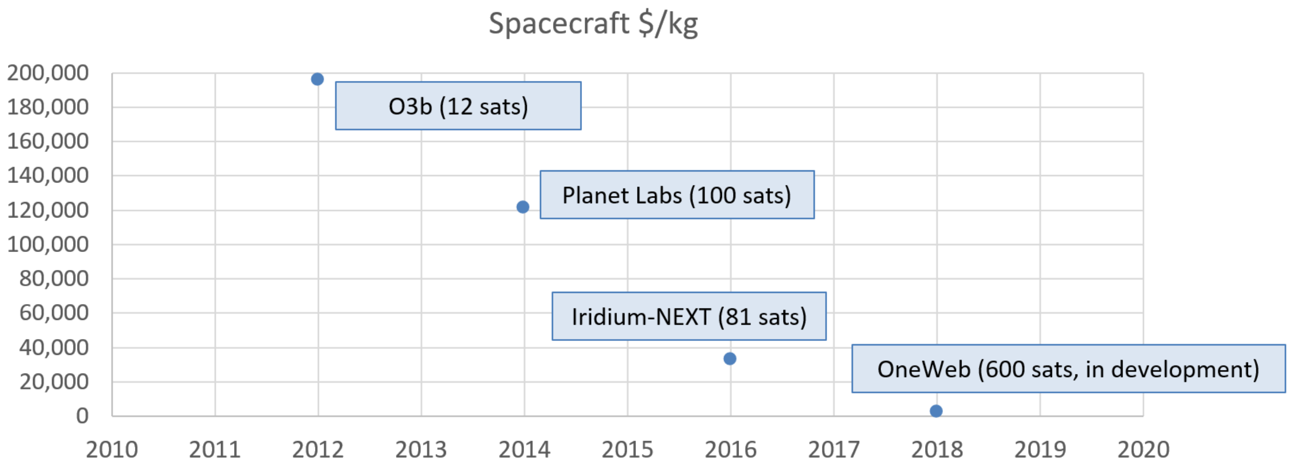

Figure J-2 – Selected spacecraft hardware costs as calculated from information appearing in SpaceNews, Spaceflight Now, and other sources. Values are scaled to be in CY2019 USD. In some instances it was not clear if costs were meant to include launch, insurance, or operations. In these cases, spacecraft cost may appear higher than actuality. Media reports often present planned costs, and may not have been updated to reflect actual costs.

The case of Planet (formerly Planet Labs) is interesting in that while the cost per kilogram appears relatively high, the cost per satellite is less than 150% of what OneWeb has baselined for their per satellite cost. This is a result of Planet's spacecraft being much smaller and lighter than typical spacecraft, and exposes the dynamic that making advances in light-weighting technology might have the effect of increasing this metric, while still indicating the progress is being made towards more practical systems for space solar. This suggests that additional space hardware cost metrics might be considered, such as $\$/m^2$ or $\$/W_{transmitted}$. However, considering $/kg in conjunction with W/kg should at least partially neutralize any misleading values, since in a complete system they will pertain to the same hardware.

Specific Power of the Space Segment (W/kg) – This metric conveys how much power can be transmitted per unit mass of the space segment. The semi log plot in Figure J-3 shows terrestrial solar conversion modules for comparison to the three solar to microwave prototypes demonstrated in recent years by the U.S. Naval Research Laboratory and a Caltech/Northrop Grumman team. Other related metrics of potential interest include kg/m^2 and combined conversion efficiency.

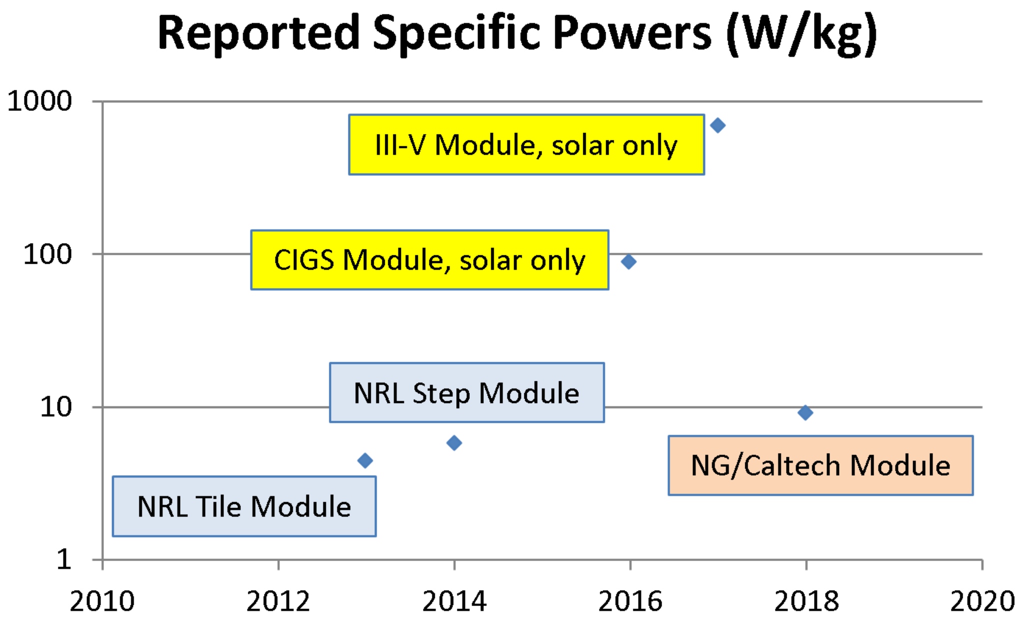

Figure J-3 – Reported specific power figures for sunlight conversion modules. NRL modules outputted 2.45 GHz, NG/Caltech module outputted 10 GHz. Solar module data from Reese et al.[16].

Cost Associated with the Receiver Segment ($/kWh) – No recent cost data was available for the costs associated with integrated power beaming receivers for microwave, millimeter wave, or laser. Dick Dickinson reported that the cost of the 1975 Goldstone microwave power beaming demonstration was "about $1/Wh,"[17] but this presumably included contributions from the transmitter system as well. This is an area where hardware prototyping, testing, and cost/performance data reporting will help address the uncertainties associated with the contributions from the receiver segment.

[16] M. Reese, S. Glynn, M. Kempe, D. McGott, M. Dabney, T. Barnes, S. Booth, D. Feldman and N. M. Haegel, "Increasing Markets and Decreasing Package Weight for High Specific Power Photovoltaics," Nature Energy, 2018
[17] R. Dickinson, Email to John Mankins, James McSpadden, and Paul Jaffe titled "wpt demos comparison", Fri 2017-09-22 4:13 PM.

APPENDIX K – ORBITS AND CONSTELLATIONS

Orbit is a major system design driver because power beaming distance drives SPS system size for a given frequency and transmitting antenna size; also, orbital period drives satellite to ground site contact time, and hence constellation design. A constellation is a set of satellites distributed over space (as distinguished from a cluster or formation) working together to achieve common objectives. Perhaps the best known is the GPS navigation satellite constellation. Its minimum required number of satellites is 24, based on the need for ground users to be able to access at least four satellites over most of the Earth for a required percentage of time.

LEO, MEO, GEO, and HEO

From a system cost point of view, the main drivers of satellite constellation design are satellite size, number of satellites, and what orbit(s) they need to be. These are interrelated because higher orbits will tend to drive satellites to larger sizes due to beam divergence, whereas lower orbits will tend to drive up the number of satellites needed for a desired ground receiver coverage duty cycle. In addition, the need to serve sites at higher latitudes may drive up total system costs, because being out of reach of geostationary satellites may require launches to higher orbital inclinations; thus lowering the capacity of launch vehicles, thereby in effect, increasing launch cost per unit mass of satellite. Although coverage time per satellite, and hence number of satellites needed for a given coverage duty cycle, can be estimated based on orbital velocity (computable once altitude is known), the actual coverage times will depend on the realities of orbital mechanics, as the satellites pass overhead and the Earth rotates beneath them. A more refined estimate of the total number of satellites needed to serve a given set of receiver sites, and total satellite access time to each FOB, will require that the total number of satellites, number of orbital planes, and the phase difference (difference in timing or true anomaly) between satellites in adjacent planes be calculated. Although configuring satellites into an optimum constellation may minimize the number of satellites, minimizing the number of planes is, by itself, unlikely to add value, because the large size of the satellites precludes multiple launch manifests. However, this could change; mass-production enables the bulk launch of large numbers of identical modules into the same plane.

For commercial grid power, the geostationary orbit (GEO) has received the most consideration. It has the advantage of remaining stationary, with respect to a given ground site. However, there is considerable beam divergence due to the distance. The design of a constellation of SPSs in GEO is relatively straightforward. The satellites would be located around the equator or within a few degrees of it at an altitude of 35,786 km, and at longitudes that will enable them to appear at a required minimum elevation angle above the horizon as seen from a given ground station. At this altitude, satellites have a period of one day, orbiting at the same rate as the Earth's rotation, enabling them to remain stationary with respect to the ground sites. Variations on GEO could involve placing the satellites in slightly elliptical, slightly inclined orbits, in which their period will still be one day. Such satellites will appear to move in a small circle, figure eight, or back-and-forth linear manner. This would allow several satellites to be "stacked" over a location where many FOBs may be located. A more extreme variation on the GEO orbit is the tundra orbit, which has a high inclination and eccentricity, and which can provide a long dwell time over high latitudes in the northern hemisphere.

A constellation of SPSs in LEO or MEO would have less beam divergence than a GEO satellite (for a given wavelength and transmitting antenna size), and may be able to supply continuous power (or at least partially overcome the limited amount of access time of a single satellite) by using beam handoffs, with multiple satellites serving multiple ground sites. However, management of the airspace around the beam and locations in space below that of the satellite would be more complex. Highly elliptical orbits (HEO), such as Molniya, may serve ground sites at high latitudes not easily reachable from GEO. HEO orbits can provide hours of contact time due to their high apogee. For LEO, MEO, and HEO orbits, there will be losses due to beam slewing [76]. In addition, for LEO, MEO, and HEO, the diameter, shape, and intensity of the beam would be continuously changing as the beam angle to the ground and the slant range from satellite to rectenna change continuously during the contact time, though this might be partly mitigated with a "smart" phased-array transmitter.

In designing a constellation, particularly for non-GEO orbits, a main driver is ground site latitude. Longitude is less important, and will come into play mainly for repeating ground track orbits at low altitudes. Latitude of the site will drive the inclination of the orbits, once an altitude is chosen. Eventually, the number of orbital planes, number of satellites per plane, and the phase difference between satellites in adjacent planes must be computed. However, with numerous orbital altitudes to be considered, and as many as several dozen ways of configuring a number of satellites in a given orbit, a systematic way of bounding the problem must be found. The analysis began by identifying a wide trade space of possible orbits. These ranged from a low inclination LEO through GEO. Some of the intermediate orbits were obtained from literature on high LEO – low MEO sun-synchronous repeating ground track orbits. The Low MEO orbit was chosen by using the altitude of one of the sun-synchronous repeating ground track orbits, combined with a low inclination consistent with a launch from Cape Canaveral. Since the inclination is not the same, it will be subject to different gravitational perturbations, and hence not be sun-synchronous, repeating ground track. Therefore, the 2,158.6 km altitude is not critical to the low MEO orbit. It was retained for ease of comparison. Another factor to be considered is the minimum elevation angle. For communications and navigation satellites, fairly low minimum elevation angles (e.g., 5° to 15°) can be considered as a rule of thumb, to avoid blockage by terrain and buildings. For space-to-Earth power beaming, it may be necessary to set a stricter requirement, because of high cosine losses due to elongation of the beam as it slews (resulting in overspillage of the rectenna), dilution of the beam as it spreads over a larger area, and attenuation of the beam as it travels through a greater air mass. In addition, some receiving sites might be adjacent to mountain ranges, so a high minimum elevation angle may need to be considered. Calculations were performed via spreadsheet to estimate access times to a first approximation. Minimum elevation angles of 15°, 30°, and 45° were considered. A coverage duty cycle of 90% at the receiving sites was considered. The results are shown in Table K-1. The orbits are illustrated in Figure K-1. Shadowing of the satellites by the Earth was not considered in the initial analysis. This could drive up the required number of satellites, particularly for lower orbits.

Table K-1 – Assessment of the number of satellites needed for different space solar constellations

Orbit Description	Apogee Altitude (km)	Perigee Altitude (km)	Circular Altitude (km)	Inclination (deg)	No. Orbits/Day	Period (min)	Maximum Time In View (min), 15 deg	Maximum Time In View (min), 30 deg	Maximum Time In View (min), 45 deg	# of Sats for 15 deg min el angle	# of Sats for 30 deg min el angle	# of Sats for 45 deg min el angle
LEO	500.0	500.0	500.0	28.5	15.2	94.6	6.0	3.5	2.1	217	375	613
Sun Sync Repeat 1	1,676.5	1,676.5	1,676.5	102.9	12.0	119.9	16.7	11.1	7.3	78	117	178
Low MEO	2,158.6	2,158.6	2,158.6	28.5	11.0	130.8	20.9	14.3	9.5	62	91	137
Sun Sync Repeat 2	2,158.6	2,158.6	2,158.6	105.9	11.0	130.8	20.9	14.3	9.5	62	91	137
Sun Sync Repeat 3	2,719.9	2,719.9	2,719.9	110.1	10.0	143.9	25.9	18.1	12.2	51	72	107
Sun Sync Repeat 4	3,383.6	3,383.6	3,383.6	116.0	9.0	160.0	31.9	22.7	15.5	41	58	84
HEO Elliptical	7,414.0	963.0	4,188.5	116.6	8.0	180.2	39.4	28.5	19.8	33	46	66
Low Van Allen Gap	7,000.0	7,000.0	7,000.0	55.0	5.6	256.7	67.8	50.8	36.1	20	26	36
High Van Allen Gap	12,000.0	12,000.0	12,000.0	55.0	3.5	413.2	127.2	97.6	70.7	11	14	19
Molniya	39,850.5	500.0	20,175.3	63.5	2.0	717.7	245.5	191.4	140.4	6	7	10
GPS	20,200.0	20,200.0	20,200.0	55.0	2.0	718.7	245.9	191.7	140.7	6	7	10
GEO	35,786.0	35,786.0	35,786.0	<1	1.0	1,436.1	531.3	418.6	310.0	3	4	5

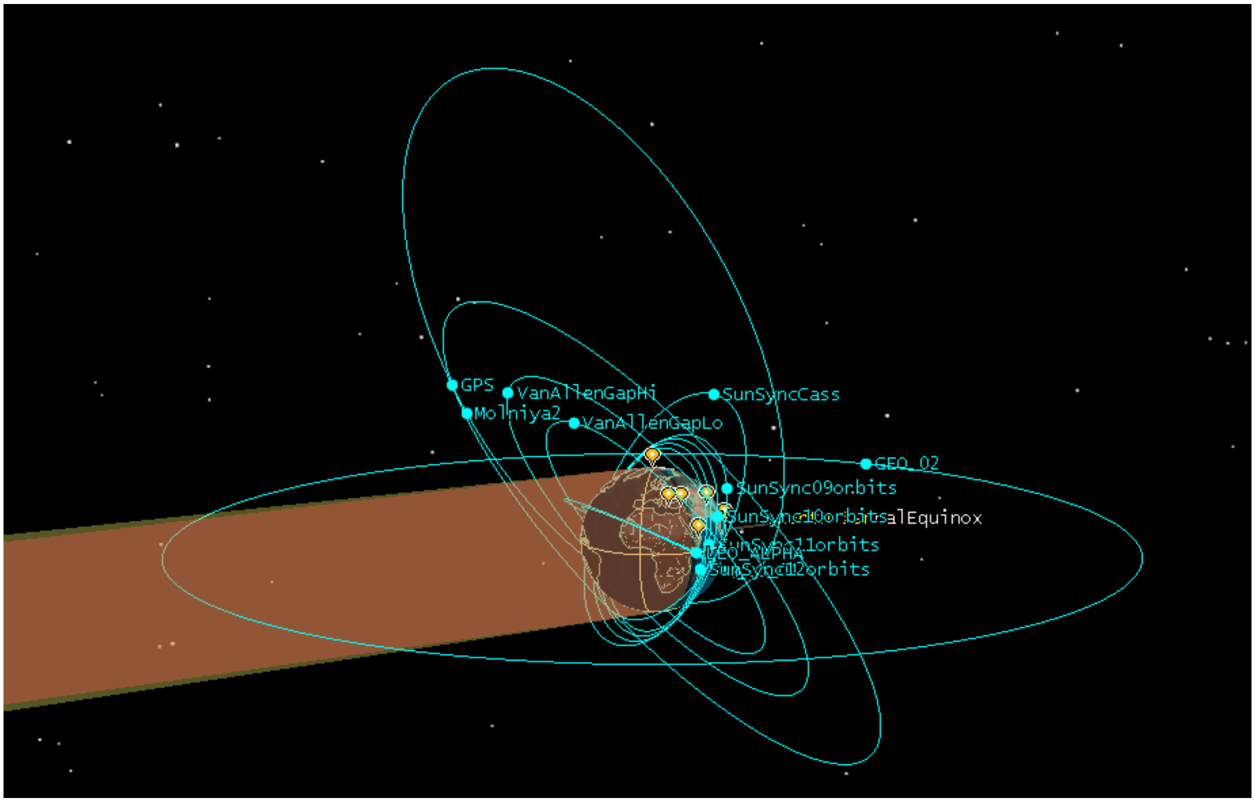

Figure K-1 – Selected proposed orbits for space solar as simulated in Systems Tool Kit

The spreadsheet model assumes that the satellites pass directly over the ground sites, and ignores the Earth's rotation. Therefore, it will tend to underestimate ground site access times for prograde orbits, and overestimate them for retrograde orbits (that is, inclinations >90°). The spreadsheet model will tend to overestimate the total number of satellites needed to achieve a given duty cycle, because it assumes only one pass per day. The latter is a user-defined input, not calculated by the spreadsheet.

A 15° minimum elevation angle leads to excessive loss due to the elongation of beam and increased slant range through a greater air mass, though the latter is not significant in clear air for frequencies less than about 10 GHz. A 45° minimum elevation angle may be too restrictive in terms of ground site access time, and may not be necessary, except for receiver sites very close to mountains. Therefore, a 30° minimum elevation angle was selected for further analysis in Systems Tool Kit (STK; formerly Satellite Tool Kit).

Downselection of Representative Design Reference Regions

The seven Design Reference Regions (DRRs) that were initially considered were downselected to three cases that span the latitude trade space, as shown in Table K-2.

Table K-2 - Design Reference Regions (DRRs)*

Design Reference Region	Location	Lat (°)	Long (°)	Elevation (m)
DRR1	Solomon Islands	-9.4	160.2	100
DRR2	Greece	36.4	25.4	100
DRR3	Afghanistan	33.2	69.6	2,200
DRR4	Somalia	9.5	49.1	410
DRR5	Colombia	2.0	-72.0	200
DRR6	Alaska	65.6	-167.9	270
DRR7	Syria	36.2	37.2	380

*The initial seven DRRs were downselected to three (shaded in green) that span the latitude trade space.

For the STK analysis, the orbits were propagated for one calendar year starting at the vernal equinox of 2028. Starting at the vernal equinox facilitated positioning of the orientation of sun-synchronous orbits. A 90% desired FOB coverage duty cycle was retained to estimate the number of satellites needed. The number of satellites needed to achieve this duty cycle was extrapolated from the total access time per year of one satellite to a given ground station.

Satellite Shadowing Analysis

A preliminary analysis of shadowing of the satellites by the Earth was considered. Shadowing analysis is complicated by the fact that shadowing typically varies by the season. Although this may preclude use of a single number to precisely define shadowing (eclipse) time for every orbit throughout the year, an estimate was derived to help further narrow the trade space.

For a 500 km, 28.5° LEO orbit, the orbital period is 94.6 minutes, and the shadowing time per orbit is roughly 28 to 36 minutes, with 35 minutes being typical; this is 37% of the 94.6-minute period.

For Low MEO 2158.6 km, 28.5°: time in shadow typically runs from about 27 minutes through about 35 minutes. Since the satellite has a 131 minute period, the maximum shadowing time would be at most, 27%, often less; so a 25% estimate is reasonable. Minimum shadowing time is zero -- that is, there are periods of several days in which the satellite is never in shadow. This happens from June 9-21 and January 14-19, though the dates are likely dependent on the initial orientation of the orbit's line of nodes. The satellite is in the Moon's penumbra for at least 44 minutes on at least one occasion. This is followed by an Earth blockage, within which another partial lunar shadowing occurs. Other moon shadowings also occur.

A previous study has shown that the sun-synchronous repeating ground track orbits for the 10, 11, and 12 orbit/day cases are in sunlight continuously. The 9 orbit/day case is in sunlight, except for a few minutes/day during December. This assumes that the ground track is over the terminator. Other orientations of the line of nodes, which are likely to be considered as constellations are developed, could result in shadowing, with a likely worst case being the noon-midnight ground track; which has a typical time in shadow of 35 minutes/orbit, as might be expected from the Low MEO case.

For the equatorial circular GEO case, as expected, the satellite will be in shadow for up to 72 minutes/day during two periods of approximately six weeks each year; around the equinoxes, around midnight local time. Analysis for the year under consideration also shows three incidences of a GEO SPS being in the Moon's penumbra for up to 67 minutes.

For the orbit cases HEO Elliptical and Molniya, the shadowing analysis has not yet been done, but may be less of a system design driver. This is because the apogee portion of the orbit, in which power beaming will take place, is likely to be in sunlight most if not all of the time.

Detailed Constellation Analysis

With 12 orbits discussed in the section above, and multiple satellites necessary for each case, depending on the FOB(s) served, the number of possible configurations of satellite constellations is large. Fortunately, the trade space of orbits can be surveyed by considering just a subset of these. Furthermore, not every orbit will be amenable to every receiver site. For example, satellites in the GEO orbit, and other low-inclination orbits, will not be visible to high-latitude sites. Elliptical orbits with their apogee over the northern hemisphere, and highly inclined orbits are more amenable to high-latitude sites, but may also have some benefit to low-latitude sites. Therefore, a satellite constellation based on a particular orbit can be optimized for a particular site (or a particular set of sites at similar latitudes), but with possible other sites benefitting as well. Therefore, the range of orbits can be narrowed.

The number of satellites needed for 90% coverage is likely to be prohibitively large for very low LEO orbits. In addition, such satellites are in shadow during a higher percentage of their orbital period than satellites in higher orbits, so that the number of satellites actually needed is likely to be even higher than shown and considerable ground and/or in-space energy storage may be necessary. Therefore, further consideration of such orbits is not warranted.

Molniya orbits, although possibly desirable for high-latitude FOBs, are constrained by a very high apogee. System sizes will likely be similar to GEO SPSs. CONOPS may be similar to SPSs in the HEO Elliptical orbit. Therefore, the HEO Elliptical case will be sufficient to gain an understanding of elliptical orbits serving high-latitude FOBs. Thus, detailed separate consideration for Molniya will not be necessary.

Table K-3 – The Orbits Shaded in Green Span the Trade Space of Solutions for Beaming Power from Solar Power Satellites to Remote Installations

Orbit Description	Apogee Altitude (km)	Perigee Altitude (km)	Inclination (deg)	No. Orbits/Day	Period (min)
LEO	500.0	500.0	28.5	15.2	94.6
Sun Sync Repeat 1	1,676.5	1,676.5	102.9	12.0	119.9
Low MEO	2,158.6	2,158.6	28.5	11.0	130.8
Sun Sync Repeat 2	2,158.6	2,158.6	105.9	11.0	130.8
Sun Sync Repeat 3	2,719.9	2,719.9	110.1	10.0	143.9
Sun Sync Repeat 4	3,383.6	3,383.6	116.0	9.0	160.0
HEO Elliptical	7,414.0	963.0	116.6	8.0	180.2
Low Van Allen Gap	7,000.0	7,000.0	55.0	5.6	256.7
High Van Allen Gap	12,000.0	12,000.0	55.0	3.5	413.2
Molniya	39,850.5	500.0	63.5	2.0	717.7
GPS	20,200.0	20,200.0	55.0	2.0	718.7
GEO	35,786.0	35,786.0	<1	1.0	1,436.1

The orbits shaded in green in Table K-3 span the trade space of reasonable solutions for SPS constellations, and can be subjected to further analysis for constellation configurations. A typical satellite constellation is likely to have a Walker delta pattern, which is an arrangement of satellites in orbits having the same altitude and inclination, with the right ascensions of ascending nodes (RAAN, or equatorial plane crossings) being evenly spaced. This will cause the satellites to be subjected to the same perturbations, and therefore, will retain the same spatial relationship with each other over time. The Walker delta pattern is defined by the total number of satellites, number of orbital planes (and therefore the number of satellites per plane), and the phase difference between adjacent satellites in adjacent planes. The latter must have a value of f*360°/t, where, for a total of t satellites in p planes, f is between 0 and p-1. If i = orbital inclination, t = total number of satellites, then the configuration of a Walker delta constellation is indicated by i:t/p/f. Another defining parameter is the spread of the right ascension of the ascending nodes (RAANs or equatorial crossings) of the planes in the constellation. This is typically 360°, thereby spreading the planes evenly around the globe, but can be less. For example, for two-plane constellations at high inclinations, a RAAN spread of 180° may be desirable; otherwise the two planes will, in effect, be nearly a single plane with satellites orbiting in opposite directions.

Low MEO constellation development

Case A:
(See Figure K-2)
<u>Orbital parameters</u>
  Altitude = 2158.6 km
  Inclination = 28.5°
  Eccentricity = 0 (circular)
<u>Constellation</u>
  Type: Walker delta with 360° RAAN spread
  Number of satellites: 34
  Number of orbital planes: 17 (hence, 2 satellites per plane)
  Phase factor: 3 (thus, true anomaly difference between adjacent satellites in adjacent planes is 3 x 360°/34 = 31.76°
  Walker notation: i:t/p/f = 28.5°:34/17/3
<u>Results for Design Reference Region 3: Afghanistan, at 33.21° latitude (attempted to optimize for this)</u>
  Access (shadowing of satellite not accounted for): 94%
  Access (shadowing of satellite accounted for): 76%
<u>Results for Design Reference Region 1: Solomon Islands, at -9.435° latitude</u>
  Access (shadowing of satellite not accounted for): nearly 100%
  Access (shadowing of satellite accounted for): 79%
<u>Results for Design Reference Region 6: Alaska at 65.56° latitude</u>
  No access

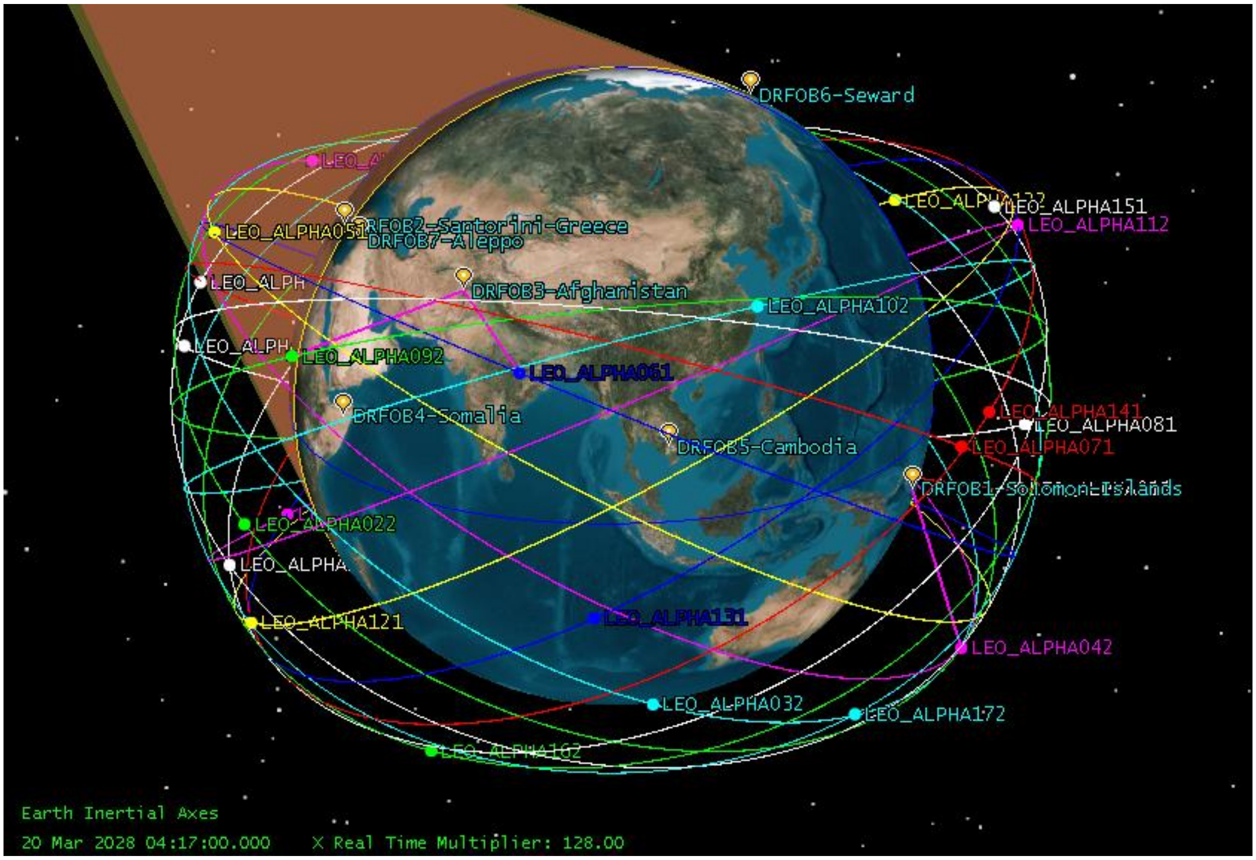

Figure K-2 – Low MEO constellation development Case A

Sun-synchronous 11 orbits/day constellation development

Case B:
(See Figure K-3)
Orbital parameters
- Altitude = 2158.6 km
- Inclination = 105.93°
- Eccentricity = 0 (circular)
- Position of initial (seed) orbit: RAAN = 90° at the vernal equinox; thus, initial orbit is around the day-night terminator, though the other plane in the constellation will be around the 12 midnight – 12 noon circle

Constellation
- Type: Walker delta, with 180° RAAN spread
- Number of satellites: 18
- Number of orbital planes: 2 (hence, 9 satellites per plane)
- Phase factor: 1 (thus, true anomaly difference between adjacent satellites in adjacent planes is 1 x 360°/18 = 20°
- Walker notation: i:t/p/f = 105.93°:18/2/1

Results for Design Reference FOB 6: Alaska at 65.56° latitude (attempted to optimize for this)
- Access (shadowing of satellite not accounted for): 75%
- Access (shadowing of satellite accounted for): 72%

Results for Design Reference FOB 3: Afghanistan, at 33.21° latitude

Access (shadowing of satellite not accounted for): 44%
Access (shadowing of satellite accounted for): 36%

Results for Design Reference FOB 1: Solomon Islands, at -9.435° latitude

Access (shadowing of satellite not accounted for): 36%
Access (shadowing of satellite accounted for): 27%

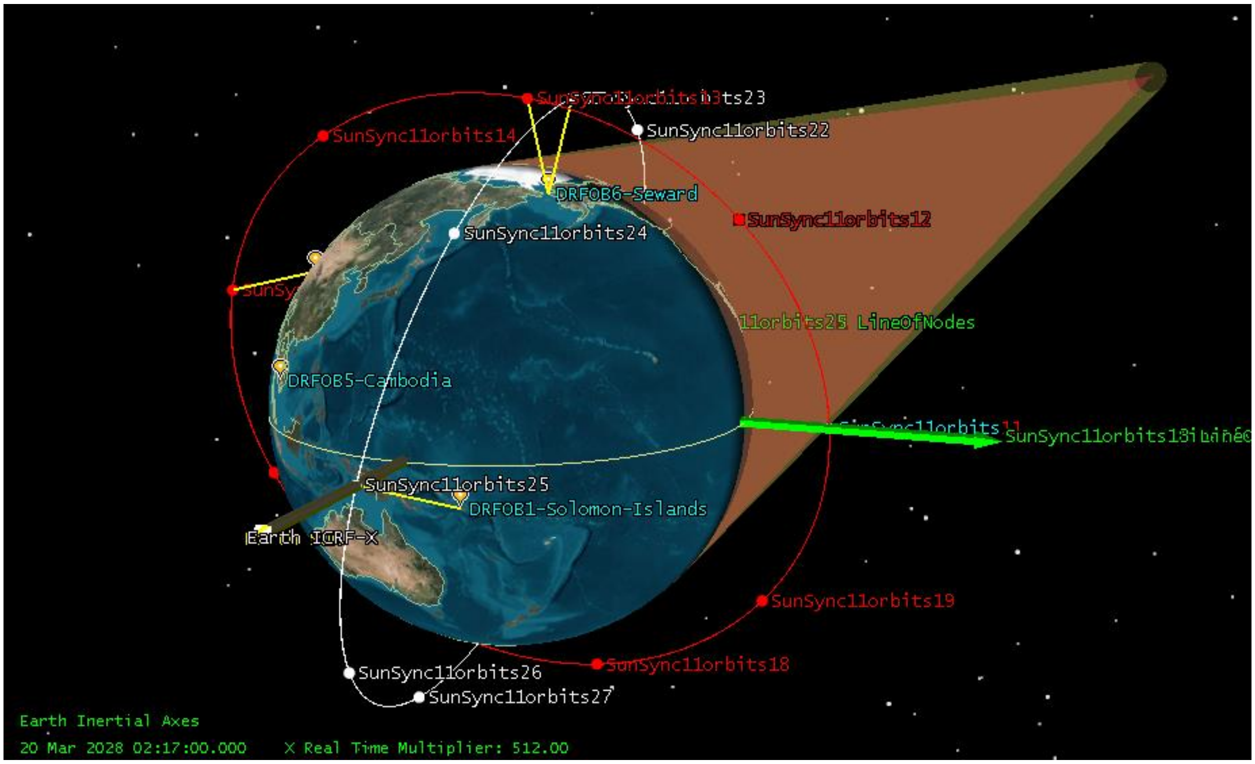

Figure K-3 – Low MEO constellation development Case B

Constellation Analysis: Preliminary Conclusions

Although more analysis needs to be done, these results have validated a methodology to survey the trade space of satellite orbits and receiver sites, and provide a reasonable estimate of the number of satellites required to achieve a required receiver site contact time duty cycle. Once cost per satellite and launch cost are established, the total cost of satellite deployment can be calculated. Coverage gaps may be filled by more satellites, energy storage on the ground, energy storage onboard the satellites, or some combination of these. A comparative cost analysis can give insight into the desired solution. Areas worthy of further investigation include other orbits, such as those in the geosynchronous Laplace plane class.

APPENDIX L – ACRONYMS

AFRL	Air Force Research Laboratory
CIO	Chief Information Officer
DARPA	Defense Advanced Research Projects Agency
DEW	Directed Energy Weapons
DLA	Defense Logistics Agency
DOD	Department of Defense
DRR	Design Reference Region
EI&E	Energy, Installations, and Environment
ETO	Earth to orbit
FBCF	Fully Burdened Cost of Fuel
FCC	Federal Communications Commission
FDA	Food and Drug Administration
FH	Falcon Heavy (SpaceX launch vehicle)
FOB	Forward Operating Base
GEO	Geosynchronous or geostationary earth orbit
GN&C	Guidance, navigation, and control
GTO	Geosynchronous transfer orbit
HEL	High Energy Laser
HEO	High earth orbit or highly eccentric orbit
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IED	Improvised Explosive Device
IEEE	Institute of Electrical and Electronics Engineers
ISS	International Space Station
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
MNPP	Mobile Nuclear Power Plants
MSIC	Missile and Space Intelligence Center
MSL	mean sea level
NASIC	National Air and Space Intelligence Center
NRL	Naval Research Laboratory
NTIA	National Telecommunications and Information Administration
OASD	Office of the Assistant Secretary of Defense
OE	Operational Energy
OEF	Operation Enduring Freedom
OIF	Operation Iraqi Freedom
ONR	Office of Naval Research
OTI	Office of Technical Intelligence
PAX	Personnel
PMAD	Power management and distribution
R&D	Research and Development
RF	Radiofrequency
RSGS	Robotic Servicing of Geosynchronous Satellites
SAMS	Space assembly and maintenance systems
SBCT	Stryker Brigade Combat Team
SERDP	Strategic Environmental Research and Development Program
SPS	Solar Power Satellite(s)
SPSS	Solar Power Satellite System
SSP	Space Solar Power

APPENDIX M – GENERALIZED SPACE SOLAR COST MODEL

Determining the Cost of Energy from Space Solar

Though numerous analyses have been performed and published for determining the cost of energy from solar power satellites, they generally have been opaque and challenging to replicate. For the utility grid space solar case, comparison has been made to terrestrial solar on a simplified and transparent cost basis by Fetter [18]. There is not currently a widely accepted means of estimating the Levelized Cost Of Electricity (LCOE) for space solar.

LCOE is a commonly used method for comparing electricity costs. Expressed in monetary cost per unit energy, such as cents per kilowatt hour, it can provide an intuitively accessible measure of how different power sources compare on a cost basis. Depending on how it is formulated, it may include the total lifecycle cost of a system and the total energy output of that system. Because it intrinsically addresses levelized costs, it does not explicitly address quantities such as total system mass or power output. As every energy source does not scale arbitrarily, LCOE provides only partial insight into system costs and considerations.

There has been extensive use of LCOE in the comparison of energy sources for the utility grid, with periodic reports provided by the U.S. Energy Information Agency (EIA). Elements that contribute to the total LCOE include levelized costs for capital, fixed operations and maintenance, variable operations and maintenance (including fuel), and transmission. The EIA publishes data for LCOEs for a wide range of sources, including coal, natural gas, solar, wind, and many others. Though there have been many reports concerning the Fully-Burden Cost of Fuel (FBCF) for military applications, a comparison of the LCOE for different sources comparable to the EIA utility grid source reports was not found in the literature.

Addressing the same elements used for typical contributions to LCOE, a rudimentary architecture-agnostic LCOE expression for space solar may be constructed:

$$LCOE_{SSP} = CAP_{SSP} + FOM_{SSP} + VOM_{SSP} + TRC_{SSP}$$

Where:

$LCOE_{SSP}$ is the Levelized Cost Of Electricity ($/kWh)

CAP_{SSP} is the levelized capital cost ($/kWh)

FOM_{SSP} is the levelized fixed operations and maintenance cost ($/kWh)

VOM_{SSP} is the levelized variable operations and maintenance cost ($/kWh)

TRC_{SSP} is the levelized transmission cost ($/kWh)

Unlike the EIA LCOE data for grid sources, none of these elements currently has a directly relevant body of data for defining a Cost Estimating Relationship (CER). Furthermore, the considerable research and development (R&D) costs remaining before the deployment of a meaningful demonstration system must be accounted for. It could be included as part of the capital cost, CAP_{SSP}, or broken out separately. In the long term, the R&D costs would be amortized, as they have been for established energy sources. Key questions: Once space solar's R&D costs are amortized, could the system produce energy at a cost competitive rate versus other sources, even for applications that might tolerate higher costs, such as defense applications? Would the benefits inherent in such a system justify the expense? While future

[18] http://drum.lib.umd.edu/bitstream/handle/1903/3992/2004-P%26S-SSP.pdf?sequence=1&isAllowed=y

technological developments cannot be predicted precisely, the LCOE expression can be used to determine where some of the thresholds might be.

For this assessment, it will be assumed that the R&D costs have been effectively amortized, with the recognition that this will take many years. The largest contributor to the $LCOE_{SSP}$ for either defense or grid space solar is likely to be CAP_{SSP}. The FOM_{SSP} may be approximated as a flat percentage of CAP_{SSP}, and the contributions of VOM_{SSP} and TRC_{SSP} can be neglected for a first order estimate. This is because the largest typical contributor to VOM_{SSP}, fuel, is not required, and space solar should be able to deliver power close to the point of need, eliminating or minimizing the TRC_{SSP}.

Numerical breakdown of four factors here

Levelized capital costs can be expressed as follows:

$$CAP_{SSP} = \frac{(CAP_{SS} + CAP_{GS})}{BCE * ATE}$$

Where:

CAP_{SS} is the levelized capital cost of the space segment ($/kWh)

CAP_{GS} is the levelized capital cost of the ground segment ($/kWh)

BCE is the beam collection efficiency (%)

ATE is the transmission efficiency after atmospheric effects and losses prior to receiver conversion (%)

The BCE is dictated by the geometry of the power beaming link: transmit and receive aperture sizes, wavelength, and range. ATE is a function of the implementation selected. Note that the conversion inefficiencies in the space and ground segments are included in their specific powers, SP_{SS} and SP_{GS}, to be described momentarily.

In turn, CAP_{SS} can be expressed as:

$$CAP_{SS} = \frac{ST_{UC} + SHW_{UC}}{SP_{SS} * SL_{SS}}$$

Where:

ST_{UC} is the cost per unit mass for space transportation ($/kg)

SHW_{UC} is the cost per unit mass for space hardware ($/kg)

SP_{SS} is the mass specific power of the space segment (W/kg)

SL_{SS} is the service lifetime of the space segment (years)

Note that ST_{UC} includes both launch from earth to orbit, and any additional cost incurred in placing the space segment in its final orbit, such as the transition from low earth orbit to geosynchronous orbit. SHW_{UC} would be expected to fall with increasing mass production, much as it has for consumer electronics and other hardware. SP_{SS} can either be calculated in the manner of Madonna[19] or measured

[19] Madonna, Richard, "Space Solar Power – What is it? Where Has it Been And What Could be Its Future?," presentation at the National Electronics Museum, May 15, 2018, Linthicum, Maryland, USA.

from prototype hardware. SL_{SS} might be expected to be on the order of 20 years or more, given the on-orbit longevity of many existing spacecraft. However, inexpensive, mass-produced modules may not have similar lifetimes.

For the contributors to the ground segment cost:

$$CAP_{GS} = \frac{GHW_{UC}}{SP_{GS} * SL_{GS}}$$

Where:

GHW_{UC} is the cost per unit mass for the ground hardware ($/kg)

SP_{GS} is the mass specific power of the ground segment (W/kg)

SL_{GS} is the service lifetime of the ground segment (years)

Using the formulations above in concert with the metrics described previously, the effects of improvements can be estimated. Table M-1 below shows five instances: one with inputs based on demonstrated values, one each for singular improvement in each of three separate metrics, and a fifth showing the influence of improvements in metrics simultaneously. Orange-shaded cells indicate model inputs. Gray-shaded cells are calculation results. Bold text indicates quantities of particular interest, and green text indicates an input that was changed from the leftmost column with the first instance.

Table M-1 – Instances of different inputs inserted into the cost model and their effects

LCOEssp	($/kWh)	$ 21.33	$ 11.92	$ 13.49	$ 1.81	$ 0.66
CAPssp	($/kWh)	$ 19.39	$ 10.84	$ 12.26	$ 1.65	$ 0.60
FOMssp	($/kWh)	$ 1.94	$ 1.08	$ 1.23	$ 0.16	$ 0.06
FOMssp%	%	10%	10%	10%	10%	10%
VOMssp	($/kWh)	0	0	0	0	0
TRCssp	($/kWh)	0	0	0	0	0
BCE	%	75%	75%	75%	75%	75%
ATE	%	80%	80%	80%	80%	80%
CAPss	($/kWh)	11.41	6.27	7.13	0.76	0.13
CAPgs	($/kWh)	**0.23**	**0.23**	**0.23**	**0.23**	**0.23**
STuc	($/kg)	**$ 10,000**	**$ 1,000**	**$ 10,000**	**$ 10,000**	**$ 1,000**
SHWuc	($/kg)	**$ 10,000**	**$ 10,000**	**$ 2,500**	**$ 10,000**	**$ 2,500**
SPss	(W/kg)	**10**	**10**	**10**	**150**	**150**
SLss	(years)	20	20	20	20	20
GHWuc	($/kg)	$ 100	$ 100	$ 100	$ 100	$ 100
SPgs	(W/kg)	5	5	5	5	5
SLgs	(years)	10	10	10	10	10

As many of the quantities have only a notional basis, these results should NOT be interpreted as a cost projection for space solar, but rather as a way of exploring the effects of different factors on prospective costs.

APPENDIX N – SOURCES OF ATTENUATION IN THE ATMOSPHERE

Gaseous Attenuation

The Earth's atmosphere attenuates electromagnetic waves in varying degrees as a function of wavelength. A qualitative representation of this effect is shown in Figure N-1.

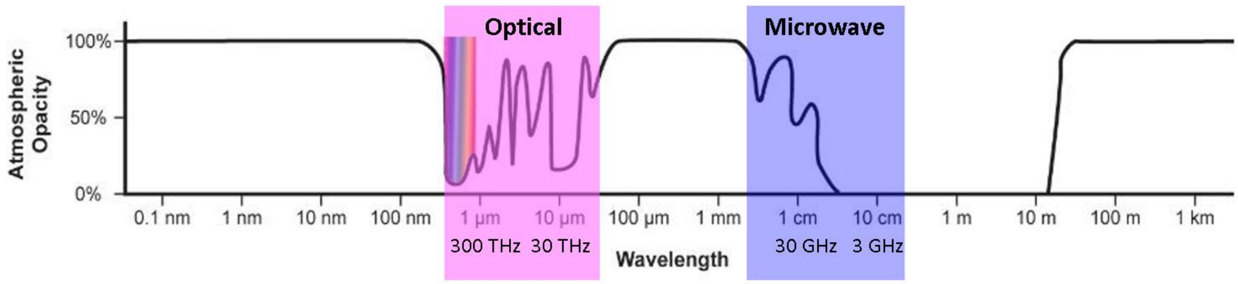

Figure N-1 – Approximate atmospheric opacity, with groups of optical transmission windows shown in pink and the microwave window of interest for power beaming shown in blue. Figure adapted from a public domain NASA image.

The losses due to scattering and absorption also increase if the wave travels a larger distance through the atmosphere, with the minimum case being straight down ("zenith"). For microwave frequencies, more precise information can be found in ITU-R P.676-11 (09/2016) *Attenuation by atmospheric gases*. Using Ontar Corporation's PcModWin5 software, the attenuation through the Earth's atmosphere can be modeled for laser wavelengths. For laser beaming power at 1.55 um and adjacent wavelengths, Figure N-2 shows the transmission efficiency under clear sky conditions at zenith. Receiving power off-zenith and/or with moisture in the air will degrade the efficiency.

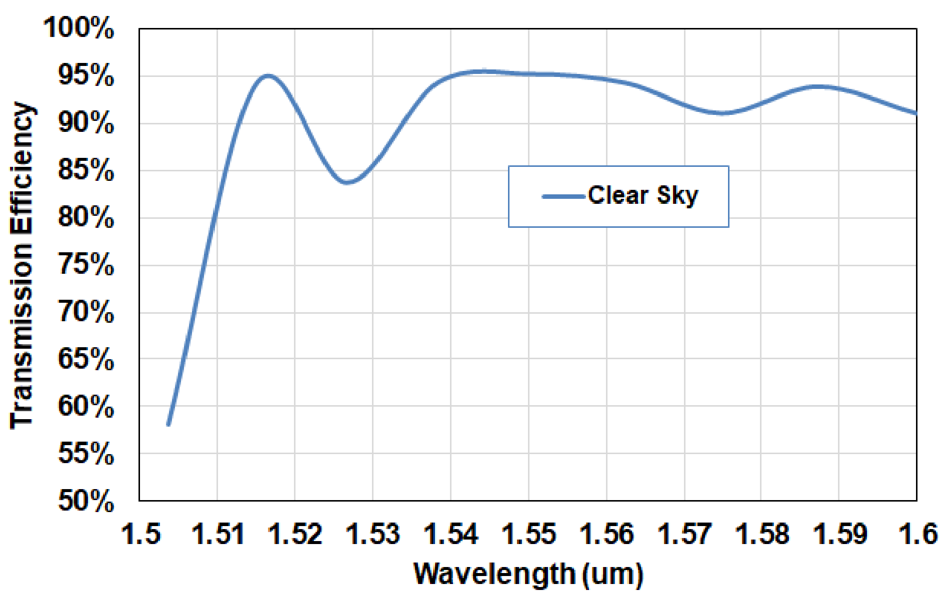

Figure N-2 - 1.55 µm laser power beaming atmospheric transmission efficiency at zenith.

Rain

For microwave power beaming at 5.8 GHz and 35 GHz, the two locations selected exhibit the highest and lowest attenuation due to rain effects of the DRRs considered for the study:

- Lowest Attenuation: Afghanistan (33.2° latitude, 69.6° longitude)
- Highest Attenuation: Solomon Islands (-9.4° latitude, 160.2° longitude)

The microwave propagation attenuation model is based on the ITU-R P.618-11 *Propagation data and prediction methods required for the design of Earth-space telecommunication systems* and ITU digital maps for rain intensity, rain height, water vapor content, and temperature across the Earth.

The analysis is based on the user's need for link availability in rain conditions, where a higher user need is defined as a requirement for the link to be available with minimal attenuation a greater percentage of the time. In this analysis, the transmission efficiency is evaluated on the number of days the Earth receiver will experience a particular rain rate. For reference, rain rate may be qualitatively considered as light (< 2.5 mm/hr), moderate (2.5 to 7.6 mm/hr), and heavy (> 7.6 mm/hr).

Figure N-3 and Figure N-4 show the transmission efficiencies through the atmosphere from GEO to a rectenna located in Afghanistan and the Solomon Islands. While 5.8 GHz has robust performance in the presence of rain, 35 GHz will have greater attenuation under similar conditions. This effect is more noticeable for the Solomon Islands, since they receive more rain annually. Any orbit or situation that requires the power beam to traverse more of the atmosphere will undergo more attenuation.

		Afghanistan								
		Attenuation (dB)		Rain Rate (mm/hr)		Time	Time	Time	Transmission Efficiency	
		5.80 GHz	35 GHz			min/yr	hrs/yr	days/yr	5.80 GHz	35 GHz
Availability (%)	80	0.05	0.3	80	5.2	105,120	1,752	73.0	98.8%	94.0%
	82	0.05	0.3	82	5.6	94,608	1,577	65.7	98.8%	94.0%
	84	0.05	0.3	84	6.1	84,096	1,402	58.4	98.8%	94.0%
	86	0.05	0.3	86	6.7	73,584	1,226	51.1	98.8%	94.0%
	88	0.05	0.3	88	7.5	63,072	1,051	43.8	98.8%	94.0%
	90	0.05	0.44	90	8.5	52,560	876	36.5	98.8%	90.4%
	92	0.05	0.53	92	10.0	42,048	701	29.2	98.8%	88.5%
	94	0.05	0.69	94	12.2	31,536	526	21.9	98.8%	85.2%
	95	0.05	0.83	95	13.9	26,280	438	18.3	98.8%	82.6%
	96	0.06	1.07	96	16.2	21,024	350	14.6	98.7%	78.1%
	97	0.06	1.47	97	19.7	15,768	263	11.0	98.6%	71.3%
	98	0.06	2.19	98	25.4	10,512	175	7.3	98.5%	60.4%
	99	0.08	4.26	99	37.3	5,256	88	3.7	98.1%	37.5%
	99.9	0.40	24.66	100	85.9	526	9	0.4	91.3%	0.3%

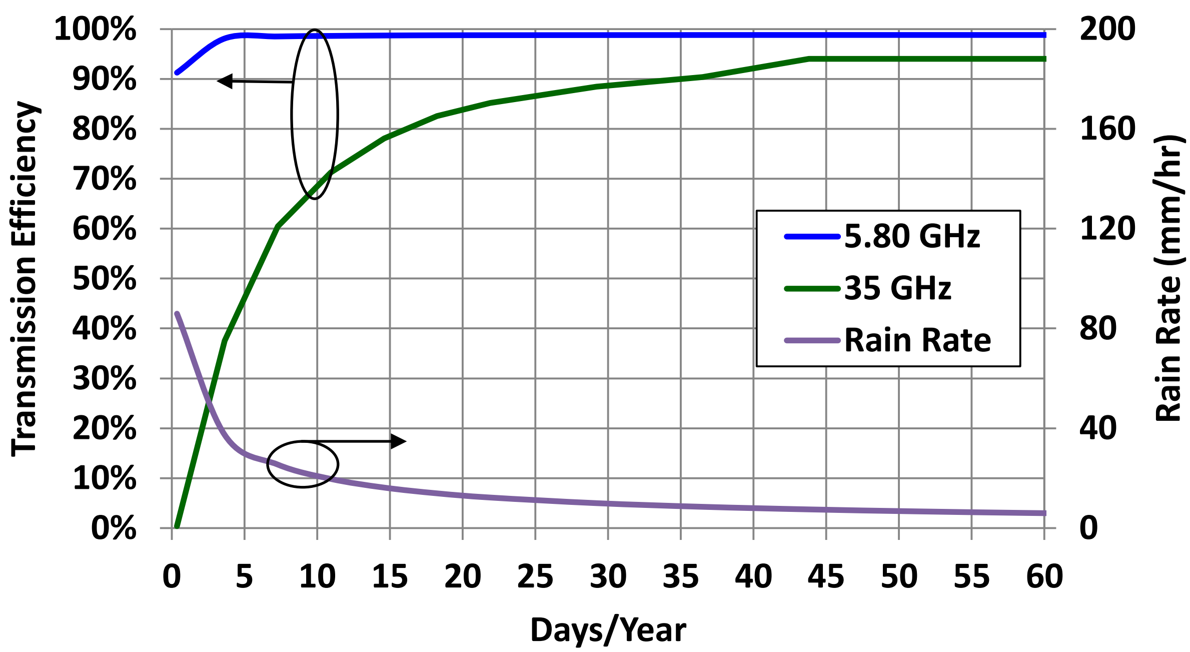

Figure N-3 - 5.8 GHz and 35 GHz power beaming atmospheric transmission characteristics from GEO to Afghanistan.

Solomon Islands

	Attenuation (dB)		Rain Rate (mm/hr)		Time	Time	Time	Transmission Efficiency	
Availability (%)	5.80 GHz	35 GHz			min/yr	hrs/yr	days/yr	5.80 GHz	35 GHz
80	0.05	0.7	80	33.7	105,120	1,752	73.0	98.8%	84.5%
82	0.05	0.8	82	36.0	94,608	1,577	65.7	98.8%	83.9%
84	0.05	0.8	84	38.7	84,096	1,402	58.4	98.8%	83.2%
86	0.05	0.8	86	41.7	73,584	1,226	51.1	98.8%	82.4%
88	0.06	0.9	88	45.2	63,072	1,051	43.8	98.7%	81.4%
90	0.06	2.55	90	49.4	52,560	876	36.5	98.6%	55.6%
92	0.07	3.14	92	54.6	42,048	701	29.2	98.4%	48.5%
94	0.08	4.05	94	61.2	31,536	526	21.9	98.2%	39.4%
95	0.08	4.73	95	65.5	26,280	438	18.3	98.1%	33.7%
96	0.09	5.69	96	70.7	21,024	350	14.6	97.9%	27.0%
97	0.11	7.15	97	77.5	15,768	263	11.0	97.6%	19.3%
98	0.13	9.80	98	87.0	10,512	175	7.3	97.0%	10.5%
99	0.20	16.01	99	103.4	5,256	88	3.7	95.5%	2.5%
99.9	1.07	80.03	100	158.0	526	9	0.4	78.1%	0.0%

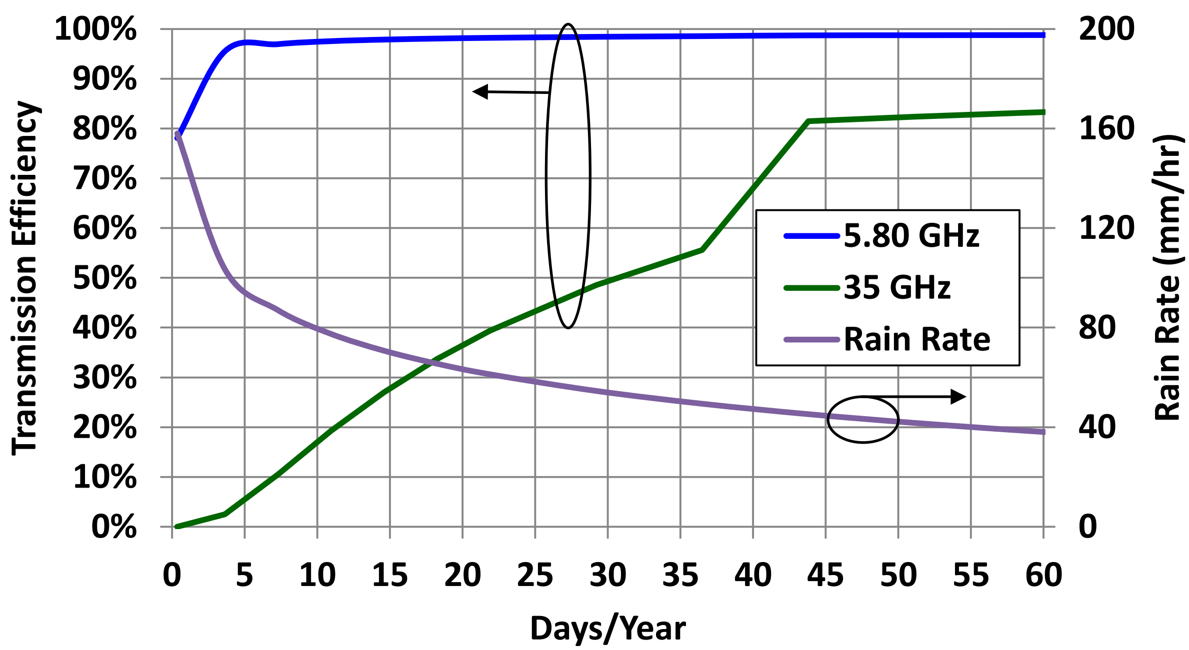

Figure N-4 - 5.8 GHz and 35 GHz power beaming atmospheric transmission characteristics from GEO to Guadalcanal Island in the Solomon Islands.

Generally speaking, any rain effects on optical transmission will be overwhelmed by the effects on transmission of the clouds associated with rain production.

Clouds

Cloud cover is highly variable, and depends on location, weather conditions, time of day, and time of year. Clouds will have negligible effects on transmission at 5.8 GHz, and generally will have only small effects on 35 GHz transmission. For laser transmission, the effect can be roughly approximated by using a map of insolation reduction due to atmospheric effects. This method will overstate the effect at higher latitudes, and does not account for the influence of different paths an optical power beam might take through the atmosphere due to orbit characteristics. A depiction of annual mean solar irradiation at the top and bottom of the atmosphere is shown in Figure N-5. Annual average attenuation is on the order of 50%, depending on location.

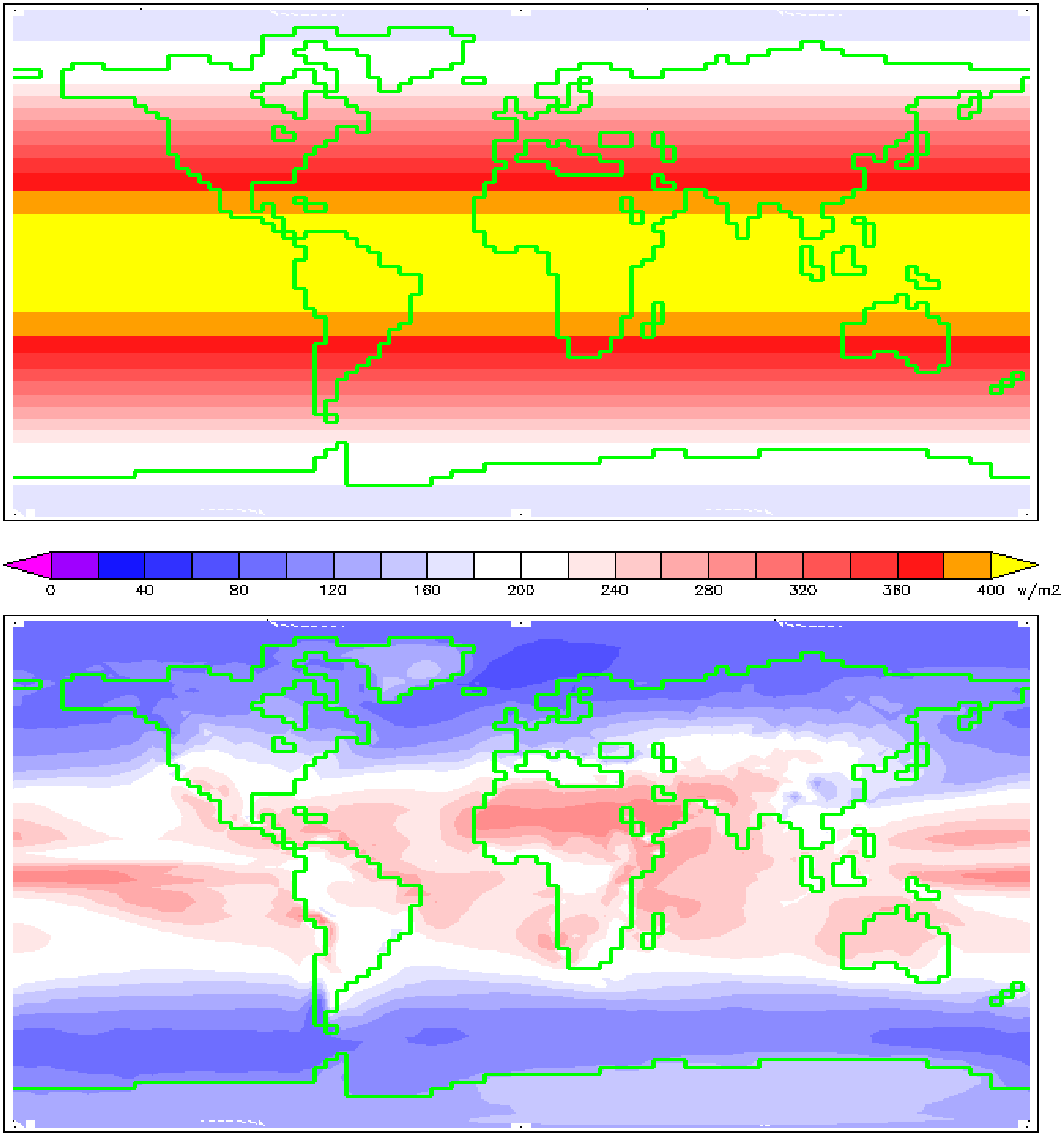

Figure N-5 - Top image shows annual mean solar irradiation (integral of solar irradiance over a year) at the top of the atmosphere; bottom image shows the value at the surface of the Earth. Data is from a climate model, not observation. Produced by William M. Connolley using HadCM3 data.

Other Forms of Precipitation and Particulates

Generally speaking, the effects of other forms of precipitation and airborne particulates will be lower compared to those resulting from rain and clouds, and are not considered in detail in this appendix. Further information can be found in ITU documents available through: https://www.itu.int/en/publications/Pages/default.aspx

APPENDIX O – FUTURE ASSESSMENT GUIDANCE
Guidelines and Recommendations for Future Studies and Assessments of Space Solar

Space solar has been studied periodically for many decades by a wide range of organizations, as evidenced by the studies available at [20]. There are literally thousands of pages of reports written on the subject. In light of this, the undertaking of any new assessment or study should clearly offer something that has not been previously examined, or should represent a reassessment based on advances in at least one key enabling technology.

It is recommended that feasibility studies address the following areas: Technological, Economic, Legal/Political, Operational/Organizational, and Schedule.

Technical
As was performed in this report, Technology Readiness Levels (TRLs) of component technologies can be evaluated. Care should be taken in determining if TRL levels could reasonably be associated with the scale of those systems needed for space solar, and in identifying which technologies are needed for particular implementations, as these often tend to be lower than others.

Economic
For both utility grid and remote installation cases, the cost of the energy provided by space solar will likely be an important consideration in determining a prospective systems' attractiveness. Any future assessment or study effort should begin by ascertaining the values of the four key metrics identified in this report: space transportation cost ($/kg), space hardware cost ($/kg), specific power of the space segment (W/kg), and the cost associated with the receiver segment ($/kWh). By determining the state of these and using the cost formulation presented, the range of possible energy costs can be outlined. Using trends for the key metrics and current and projected LCOEs for alternatives, a potential cost comparison can be performed. Note that thresholds of feasibility will vary depending on mission and the evolution of technology alternatives.

Legal/Political
Future assessments should examine if there has been any progress in spectrum identification or allocation for microwave power transmission, and whether there have been international political developments that would favor or disfavor the placement of laser transmitters in orbit.

Operational
As has been observed in this and previous studies[21], power density plays a critical role in terms of both safety and utility. Any new developments in the areas of safety or technology that affect the power density levels that can be realized that the receivers, whether based on the ground, sea, at altitude, or elsewhere should be carefully considered.

Schedule
Any future assessment should consider what timeframe a system could realistically be implemented based on recently demonstrated systems or reasonable extrapolations.

[20] https://space.nss.org/space-solar-power-library/
[21] https://apps.dtic.mil/docs/citations/ADA513123

APPENDIX P – U.S. DEPARTMENT OF DEFENSE TECHNOLOGY READINESS LEVELS

(Source: DoD (2010), Defense Acquisition Guidebook)

Technology Readiness Level	Description
1. Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2. Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3. Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4. Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.
5. Component and/or breadboard validation in relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.
6. System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment.
7. System prototype demonstration in an operational environment.	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space. Examples include testing the prototype in a test bed aircraft.
8. Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9. Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

Available: https://www.army.mil/e2/c/downloads/404585.pdf