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A STUDY OF SPACE-BASED SOLAR POWER SYSTEMS

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MONTEREY, CALIFORNIA

THESIS

A STUDY OF SPACE-BASED SOLAR POWER SYSTEMS

by

John P. Pagel

September 2022

Thesis Advisor: Bonnie W. Johnson
Co-Advisor: John M. Green

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13. ABSTRACT (maximum 200 words)

Space-Based Solar Power (SBSP) is best defined as delivering meaningful amounts of energy without moving or employing mass between the transmitter and receiver. The current modus operandi for the Department of Defense (DOD) requires the delivery of energy by physical transport of fossil fuels or its derivatives, which is burdensome, costly, and dangerous in the face of threats.

SBSP is known to be technically possible, with varying degrees of success, from ground-based wireless power transmission demonstrations; integrated solar collection, conversion, and transmission systems development; and microwave conversion and rectifying efficiency studies, but a full end-to-end SBSP system has yet to be realized.

This thesis aims to explore SBSP's utility in DOD operations at the tactical edge, serving the warfighters at forward operating bases as well as expeditionary forces where power infrastructure is problematic or extant. A collection of SBSP research, studies, and articles was pored over to identify the major stakeholders for such a system, analyze their requirements, and identify a valid reference architecture to maximize the SBSP solution space.

This thesis's conclusive results can serve as a baseline for further research in this field. The international community is already aggressively underway in SBSP system design, and the results herein highlight the need for the DOD to act as a leader in this space decisively and quickly.

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A STUDY OF SPACE-BASED SOLAR POWER SYSTEMS

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Submitted in partial fulfillment of the
requirements for the degree of

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LIST OF ACRONYMS AND ABBREVIATIONS

AC	Alternating Current
AFRL	Air Force Research Laboratory
AKA	Also Known As
ASAT	Anti-Satellite
AT/FP	Antiterrorism / Force Protection
C2	Command and Control
CONOPS	Concept of Operations
DA-ASAT	Direct Ascent Anti-Satellite
DC	Direct Current
DOD	Department of Defense
DoE	Department of Energy
ERDA	Energy Research & Development Administration
FOB	Forward Operating Base
GEO	Geostationary Equatorial Orbit
GTO	Geostationary Transfer Orbit
ICOM	Inputs, Controls, Outputs, and Mechanisms
INCOSE	International Council of Systems Engineering
iSA	In-Space Assembly
ISS	International Space Station
ITU	International Telecommunication Union
JAXA	Japan Aerospace Exploration Agency
kW	Kilowatt
LEO	Low Earth Orbit
MW	Megawatt
NASA	National Aeronautics and Space Administration
NFC	Near Field Communications
NRL	Naval Research Laboratory
NSSO	National Security Space Office
OECIF	Operational Energy Capability Improvement Fund
OPTEMPO	Operational Tempo

PRAM	Photovoltaic RF Antenna Module
PTROL	Power Transmitted Over Laser
PV	Photovoltaic
RF	Radio Frequency
RFID	RF Identification
SBSP	Space-Based Solar Power
SME	Subject Matter Experts
SOC	Satellite Operations Center
SPS	Solar Power Satellite
SPS-ALPHA	Solar Power Satellite - Arbitrarily Large Phased Array
SSPIDR	Space Solar Power Incremental Demonstrations and Research
SSPS	Space Solar Power Station
TRL	Technology Readiness Level
TT&C	Telemetry, Tracking, and Commanding
USMC	United States Marine Corps
USSF	United States Space Force
VAC	Volts Alternating Current
W	Watt(s)
WPT	Wireless Power Transmission

EXECUTIVE SUMMARY

United States (U.S.) military operations are dependent on electrical energy to power systems, ranging from weapons, ships, aircraft, communications, and intelligence-collection to quality-of-life amenities like heating, ventilation, air condition, and coffee machines. The ability to power these systems is a critical enabler of military operations spanning peacetime, conflict, and war. Because these day-to-day activities are governed by electrical power availability, an innovative solution for electrical energy distribution would be a game-changing technology deserving of highly prioritized investments. The outcome of such investments would be a boon to all military equities with collateral benefits to humanitarian efforts and ultimately the planet itself.

The U.S. Department of Defense (DOD) is engaged in efforts to become more energy-efficient in support of Executive Order 14008, "Tackling the Climate Crisis at Home and Abroad," which includes a U.S. goal of net-zero greenhouse gas emissions by 2050 towards which the DOD is actively developing technologies and roadmaps. Fossil fuels are ancillary to the energy distribution that vitalize military systems and come with detrimental baggage like harmful environmental impacts and troublesome transport. A revolutionary innovation that avoids these negative effects is space-based solar power (SBSP) which harnesses the sun's persistent radiance and channels that energy into a directed stream of wireless power. Gone would be the inconvenience, danger, and high expenses that accompany energy resupply for forward-deployed forces. Less focus would be divested from the warfighter's mission itself but rather funds could be redirected to other ventures supportive of missions directly, notwithstanding the beneficial side effects to humanitarian efforts and the environment.

The innovation of SBSP lies in the wireless power transmission from space, where solar energy collection is done free from inefficiencies caused by an atmosphere or physical coverage, and converted to microwave signals. This power source can be pointed to any target location in the world effectively providing clean energy that is near-constant and on-demand. There are numerous research studies and demonstrations from national institutions, Naval Research Laboratory the chief among them, that have demonstrated

terrestrial laser power transmission, wireless network signal power transmission, and sunlight conversion to microwave in space. These all play a part in furthering the SBSP concept.

Once realized, SBSP can directly support DOD operations at strategic and remote locations absent of existing power infrastructure. Forward operating bases are stood up in these locations typically with large areas to support air logistics along with reconnaissance and surveillance teams. Due to their nature, power demands are unpredictable and can be exacerbated with joint or multi-coalition personnel coming and going. The fuel resupply of a remote base invites risks to soldiers, vehicles, and equipment, and can be timely and costly because of the amount of fuel required to execute the actual fuel delivery. Incorporating the SBSP system into base planning and operations eliminates the risks associated with fuel resupply because generator fuel is unnecessary. Additionally, SBSP can be combined with hybrid energy solutions like terrestrial solar and wind to provide more flexibility in the DOD's energy architecture for forward operating bases. The persistent power transmission also provides for more power-hungry autonomous systems to be considered in future operations, reducing the number of troops on the ground and associated amenities and logistics needed for subsistence and quality of life.

This thesis conducted a systems engineering analysis approach, beginning with a literature review that focused on conceptual origins of SBSP. Its roots started with an early patent for wireless power transmission that can be traced to the most recent demonstrations for SBSP capabilities. This literature review also delved into some of the ongoing international efforts that can be viewed as opportunities for or contention to the goal of U.S. space superiority. Next, a qualitative needs analysis was conducted that included the identification of stakeholders and a discussion of how those needs are addressed by a future SBSP system. Based on that assessment, functional and performance requirements were defined and analyzed with considerations to the SBSP system's life cycle. Finally, the SBSP system's architecture was proposed, stemming from the requirements definition process, whereby an operational analysis was performed to develop high-level concepts of operation.

The potential benefits of SBSP are vast because of its disruptive technology. This thesis touches on the benefits towards the Net Zero goal of removing the amount of greenhouse gases coming into the atmosphere. This thesis also distinguishes SBSP as a complementary source of power to terrestrial solar as opposed to a competing one. Lastly, this thesis recognizes now as an inflection point in determining the U.S. role in SBSP development and dependency and highlights adversarial uses to encourage U.S. investment in SBSP so it can be at the forefront of power beaming technology. Some challenges are also addressed that range from the technological, economical, and political that without resolution, will keep a SBSP out of reach.

This thesis is meant to serve as a baseline top-level analysis for a SBSP system design that has been recognized as having no fundamental technical barriers. SBSP is not impossible, and a full-scale system is very much in the realm of realization within the next three decades. The information presented herein is meant to be used to foster research in SBSP and enabling technologies (e.g., in-space assembly, space robotics, and solar conversion efficiencies). It is imperative for the U.S. to include SBSP in future operations planning because the military applications would be monumental to the warfighter, with the reduction in logistics, fuel, and safety risks associated within, complementing the DOD energy architecture, and promoting the use of autonomous systems in place of troops on the ground in high-threat environments. Without further research into this topic, the DOD stands to lose its competitive edge in the energy space, surrendering its superiority as other countries like China accelerate their understanding. There are known risks in space superiority, warfighting capability, and even diplomacy for not leading in this space that would propagate a negative impact to U.S. interests.

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Lastly, but not least, to my pulchritudinous children, Leon and Louis. Their humor and boundless curiosity have kept me engaged and reminded me for whom I comported all my industrious efforts. They have afforded me the full spectrum of temperaments, giving me incredible experience in forbearance and unconditional love. May they continue showering their lessons upon me and ameliorate my shortcomings. I love them so much!

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I. INTRODUCTION

There is an ever-present need for the Department of Defense (DOD) to continue leading the edge in space dominance and thusly, space innovation. Their priorities for the space domain were laid bare when the United States established the U.S. Space Force (USSF) in December of 2019 as a new military service. Did they even consider the architects of the Pentagon? Was there any thought in how thrusting the “Hexagon” namesake upon such a favored building would be accepted? I digress.

The White House communicated these new investments with a published framework that highlight foreseeable benefits, some of which touch on new frontiers in clean air technology and addressing the climate crisis. It goes on further to underpin national security with the ambition to remain the global leader in space science and engineering (The White House 2021, 3–4). To stay true to this pioneering spirit, there is no technology more ripe for dividends that fulfills the advertised framework than space-based solar power (SBSP) technology.

Furthermore, it is evident that the use of finite fossil fuels like coal, crude oil, natural gas, or derivatives thereof is simply not sustainable for any long-term horizon and the DOD recognizes them to be used as a bridge to more sustainable alternatives (Jaffe 2019, 7). It also becomes problematic as the DOD conducts forward-basing operations to further national interests. Energy consumption is mandatory for forwardly deployed warfighters to succeed, and some of these missions may be devoid of existing power infrastructure or reliable energy resources.

SBSP aligns directly with the U.S.’s intent to prevail as the global space leader and address the continual increase in military power systems’ requirements for persistent, reliable energy.

A. OVERVIEW

SBSP is the wireless transmission of power from space to Earth’s surface. This game-changing technology is not an entirely new concept, with several authors on the subject demonstrating its possibility as well as communicating aspects of its feasibility.

Therein lies the challenge of engineering a SBSP system, which is known to be possible, but with an end-to-end efficiency satisfactory to the DOD. SBSP provides power to the warfighter with no temporal limitations and anywhere on Earth's surface. The warfighter today is heavily dependent on reliable power. As their electrical energy demand continues its uptrend, there are only a few large-scale energy generation options poised to meet that need (Barnhard and Potter 2018) and be the paradigm shift that the DOD yearns for to revolutionize operations-related energy generation and consumption.

B. RESEARCH OBJECTIVE

The objective of this thesis is to develop a conceptual SBSP system architecture based on projected user needs and expected capabilities. The research will explore the potential capabilities of SBSP based on literature review and will identify military applications that would benefit from the future innovative capability that has yet to be implemented to scale by any organization within or external to the DOD.

C. SCOPE AND RESEARCH APPROACH

The scope is limited to the beginning stages of understanding the SPSP system, applying the systems engineering rigor most beneficial to technologies before they perforate their emergent status into ubiquity. This includes an analysis on DOD energy requirements and feasible system architectures that would best apply to DOD use cases.

The thesis will follow a systems analysis approach according to the following steps:

- Literature review to understand potential SBSP capabilities
- Identification of possible military applications
- Stakeholder needs analysis and system requirements analysis
- Development of a conceptual SBSP system design and architecture
- Concept of operations analysis for SBSP system applied to identified military applications
- Assessment of SBSP benefits and challenges

D. THESIS ORGANIZATION

The thesis is organized logically into five chapters. Chapter I introduces the thesis and provides the research objective and approach. Chapter II contains the literature review which describes the potential capabilities of SBSP as an innovative technology. Chapter III contains the system analysis, including the stakeholder needs, system requirements, conceptual designs and architecture, and Concept of Operations (CONOPS) analysis. Chapter IV presents the results of an assessment of the SBSP system's potential benefits and challenges. Finally, Chapter V concludes the thesis, summarizing the research and providing recommendations for future work.

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II. LITERATURE REVIEW

This literature review presents an overview of the SBSP system and some of its earlier concepts from subject matter experts (SMEs). It will touch on the needs documented by the DOD and how the SBSP system addresses these needs directly, affording the DOD a more capable warfighter with significant long-term savings.

A. SPACE-BASED SOLAR POWER

The SBSP system collects solar radiation to convert it into radio frequency (RF) signals that can be transmitted from space down to Earth's surface for receipt and conversion to alternating current / direct current (AC/DC) power. The innovative aspect of this technology is the wireless transmission of electrical energy at a much larger scale than what we have today. Transmission through free space is highly desirable over great distances (>100 km) because it is far more efficient than contemporary solutions like copper or fiber optic cables. The system consists of two parts: the space segment, or Solar Power Satellite (SPS), where the solar radiation collection and power beam transmission takes place, and the ground segment, or Receiving Station, that accepts the beam and converts the RF signal to DC power.

The SBSP system is a concept that can be traced back to Nikola Tesla's early patent of wireless electrical transmission, US645576, whereby electrical energy can be propagated through the Earth and air strata to be received at a distant point (U.S. Patent Office 1900). Figure 1 is an illustration of Tesla's contemplations showing the left apparatus transmitting power from D at a sufficient elevation for power transmission to D', powering lamps L and motors M at the receiving station on the right. Though it did not amount to anything useful immediately after, this set the stage for all the conveniences of wireless transmission that we enjoy today, like RF identification (RFID) and near-field communications (NFC). These technologies generate magnetic fields that can induce electrical currents without the use of wires much like we find in hotel or parking garage key cards.

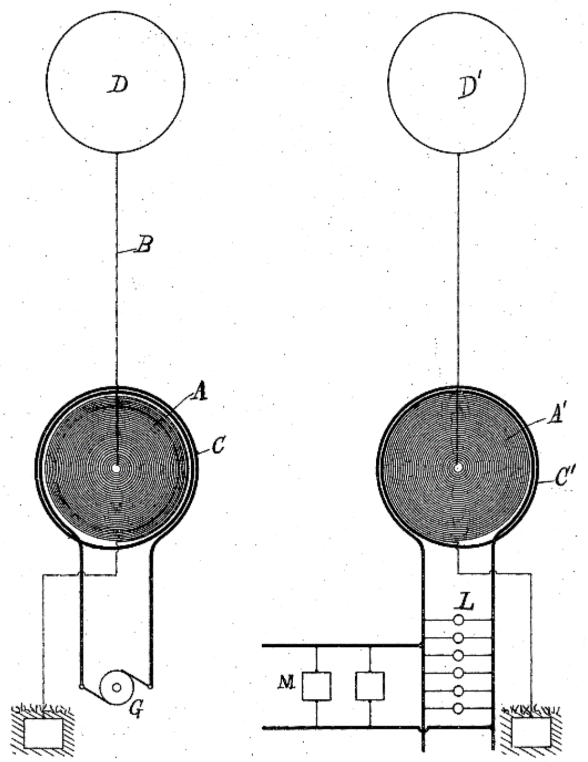

Figure 1. Patent US645576, System of Transmission of Electrical Energy by Nikola Tesla. Source: U.S. Patent Office (1900).

Fast forward to 1973 when Dr. Peter Glaser took Tesla's concept further and patented electrical transmission using microwave energy from solar collection in space (Glaser 1973). Figure 2 shows this early concept and the patent illustratively outlines the solar array estimating to be 25 square miles and the phased-array planar antenna to be 0.5 square kilometers. Even the earliest concept recognizes the sheer magnitude of physical dimensions that dictates every aspect of the system, so far as mentioning a 36 square mile receiving zone. These spatial requirements alone can obscure the practicality of such a system, but SMEs expand upon this patented idea and quickly find some merit.

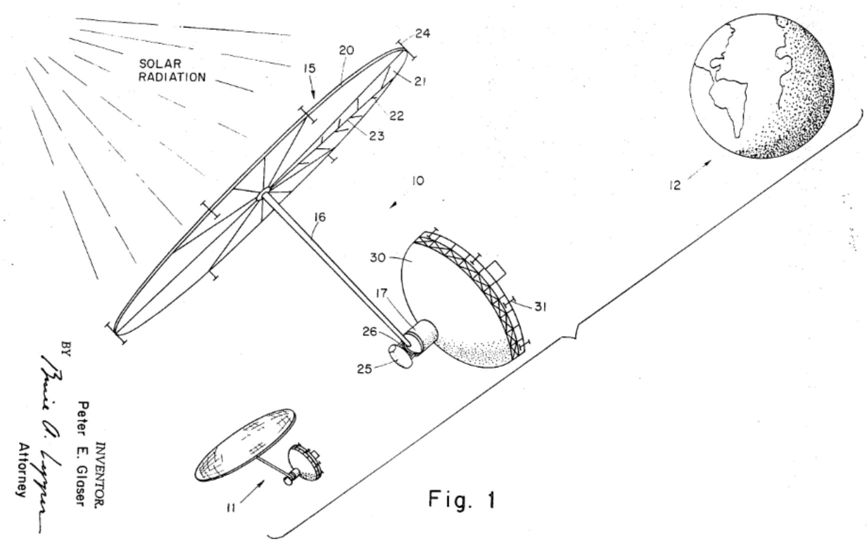

Figure 2. Patent US3781647, Method and Apparatus for Converting Solar Radiation to Electrical Power. Source: Glaser (1973).

Spatial dimensions aside, numerous concepts and architectures from Naval Research Laboratory (NRL), Air Force Research Laboratory (AFRL), DOD National Security Space Office (NSSO), and National Aerospace and Aeronautics Association (NASA) elucidated Dr. Glaser's concepts and elaborated more upon underlying components. Technological advancements over time have removed some of the barriers that stand in the way of full-scale SBSP investments, like reusable and less costly launches and solar cell efficiency, but there are still others working against the feasibility of a realized SBSP system.

B. TECHNOLOGY TO DATE

Though the U.S. "was a pioneer [on] this [front], its small and sporadic projects could become overshadowed by increasing international efforts" (Jones and Vedda 2020, 307). Unfortunately for the U.S., their deceleration of investment into SBSP technologies is noticeable on the global stage. Other nations are putting serious resources into advancing this capability to their own ends. There is obvious value in SBSP from within and outside of U.S. interests and some of the major efforts from all parties involved include the following.

a. Research and Studies

NASA began their research on the topic dating back almost 50 years ago, when they evaluated over 30 kW of DC power using microwave transmission over a distance of 1.54 km (Dickinson 1975). They essentially showed that a highly efficient receiving mechanization for a microwave transmission link was possible.

NASA also partnered with the Energy Research & Development Administration (ERDA), now known as the Department of Energy (DoE), to include a SPS as part of their alternative energy studies in the 1970s (Jones and Vedda 2020, 308). In 1995–1996, NASA reviewed their past research on the topic and updated their findings in their “A Fresh Look at Space Solar Power” report, which examined the space segment of a SBSP system as a viable alternative to terrestrial electrical power from a holistic perspective, covering positions like economic, environmental, and safety (Mankins 1997).

Another notable report was about an analytical design dubbed “Solar Power Satellite Arbitrarily Large Phased Array” (SPS-ALPHA), which included a holistic approach to analyzing technology readiness and economic viability using thin-film mirrors at Geostationary Equatorial Orbit (GEO). Figure 3 shows a version of this concept that illustrates its complexity, with the eye-catching thin-film mirrors arranged to act as a very large sunlight-intercepting reflector system. The main goal of this project was to advance “the SPS-ALPHA concept to an early [Technology Readiness Level] (TRL) 3—analytical proof-of-concept—and to provide a framework for further study and technology development” (Mankins 2012, 6). The report concluded that the SPS-ALPHA would be capable of delivering $0.09/kWh electricity and fulfilling a promise of full-scale viability for an SBSP system with no needed technological breakthroughs at the time.

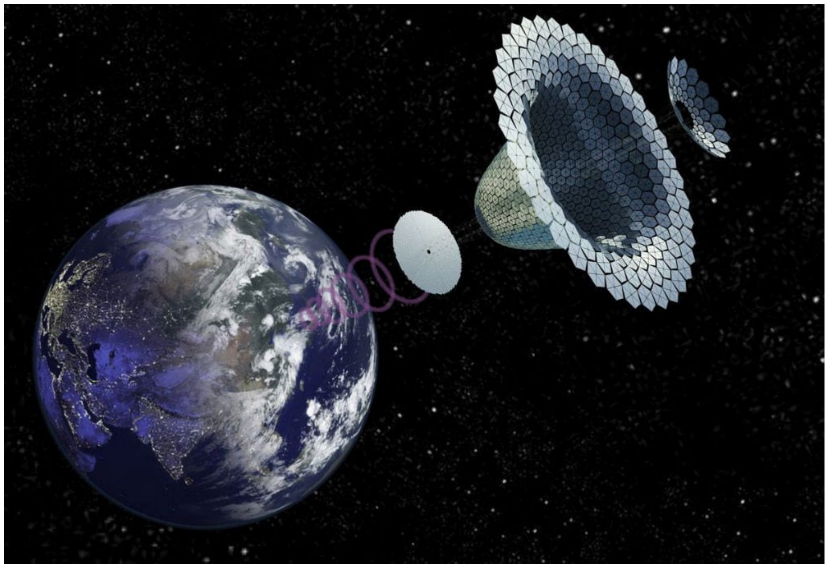

Figure 3. Version 1 of the SPS-ALPHA Concept. Source: Mankins (2012).

b. Demonstrations

The NRL has been involved in a variety of different projects that have taken incremental steps in showing the feasibility of SPS functionalities. They conducted a successful demonstration known as Power TRansmitted Over Laser (PTROL), which used an infrared laser to transmit power across the Earth's surface in 2019. They also conducted an experiment, Lectenna, at the International Space Station (ISS), which used a light-emitting rectifying antenna (rectenna) to convert a wireless network signal into electric power in 2020. In that same year, NRL also helped launch the first orbital SBSP-related experiment on the X-37B space plane to test a sub-system module, Photovoltaic RF Antenna Module (PRAM), "by converting sunlight to microwaves outside the atmosphere and analyzing the energy conversion process and resulting thermal performance" (Jones and Vedda 2020, 308).

AFRL has a series of incremental demonstrations dubbed their Space Solar Power Incremental Demonstrations and Research Project (SSPIDR). Their main aim is to prove and mature essential technologies for a prototype SBSP transmission system capable of powering a Forward Operating Base (FOB) (AFRL 2021). FOBs are one of the best use cases for SBSP because they are nestled in strategic and remote locations with reliance on power and logistical support, all of which can be serviced by SBSP. AFRL has broken out the series of demonstrations into six critical technologies to help validate both the technology concepts and models for integration into a full SBSP system. The technologies touch on thermal challenges, energy generation and RF beaming, and deployable structures technology, all of which are key to enabling SBSP. Figure 4 shows an artist's rendition of Arachne, SSPIDR's keystone flight experiment that is expected to launch in 2025.

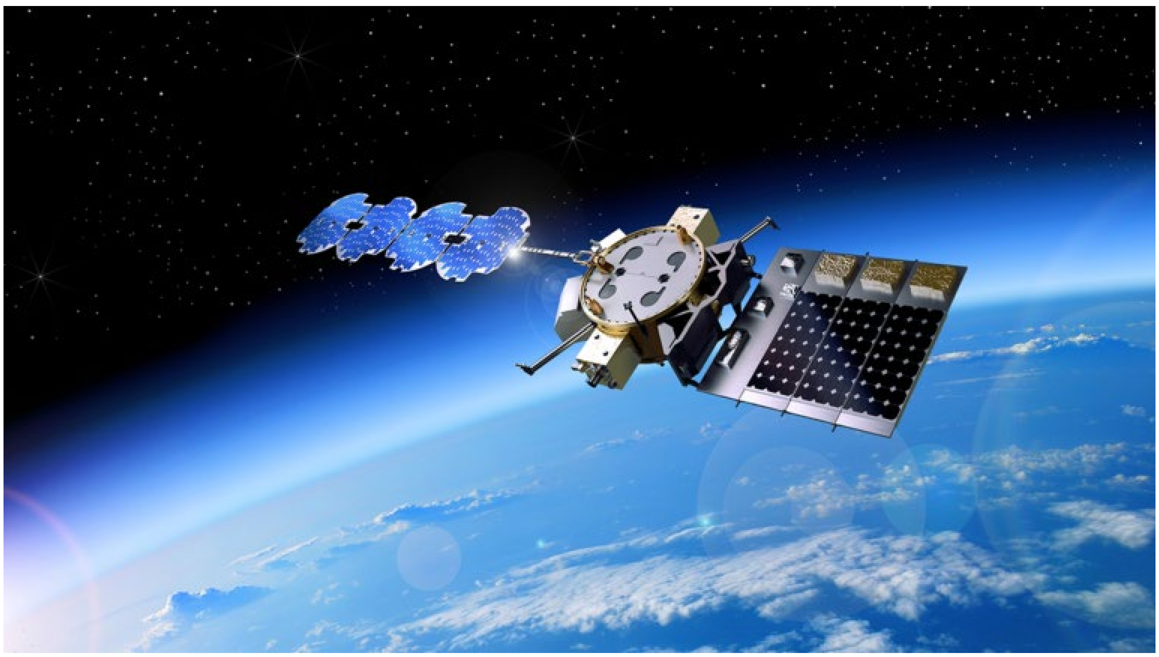

Figure 4. Artist's Image of Arachne, an Experimental Solar Power Satellite. Source: AFRL (2021).

c. *International Innovations*

The Japanese Aerospace Exploration Agency (JAXA) have made steady research investments in SPS since the late 1990s, developing two conceptual designs: the SPS2000, which focuses on a Low Earth Orbit (LEO) constellation, and SPS2004, which is a GEO-based SPS with rotating solar collection mirrors (Jones and Vedda 2020, 309). The roadmap they developed in 2014 advertised a clear path in improving conversion efficiencies, reducing size and weight of electronic modules, and enhancing microwave beam-pointing control, all with the purpose to provide a combined capacity of 1 GW by 2030.

Figure 5 shows the JAXA Space Solar Power System (SSPS) in action, impervious to cloud cover and rain, all the while offering a stable supply of power for a city below. A major innovation contributing to a fully functional SBSP system are glass-resin laminates resulting in ultra-thin lightweight mirrors. This is key for the SSPS because its mirrors will stretch 3.5 km across space, so lightweight cargo is necessary for reducing launch requirements (Nippon Electric Glass 2022). JAXA incorporated these mirrors in a 2011 prototype in preparation for their 2030 vision.

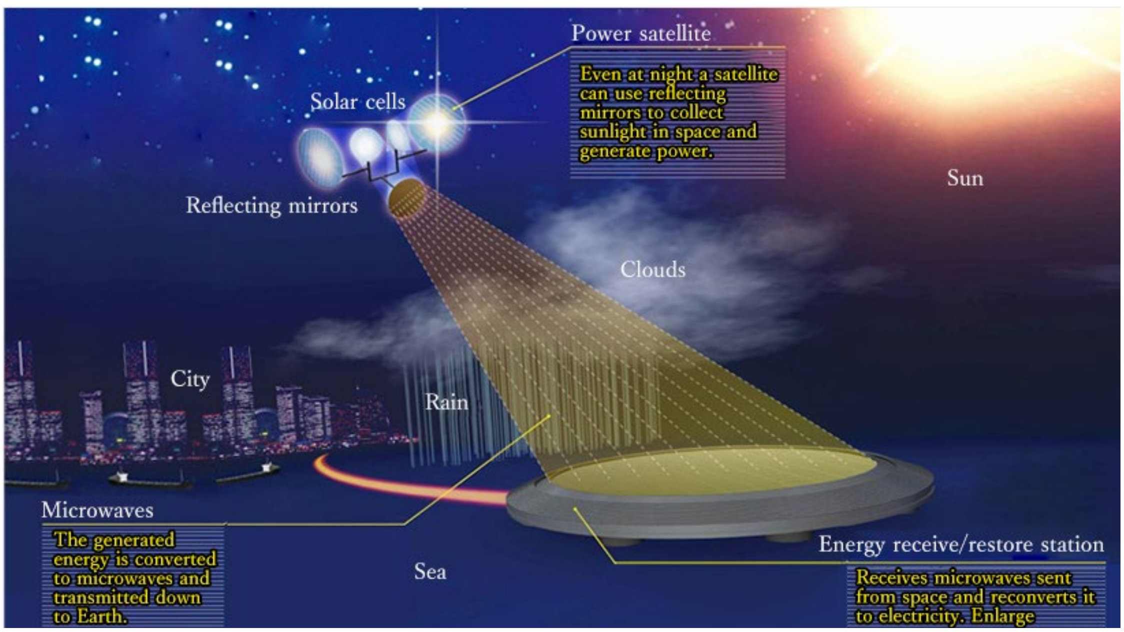

Figure 5. JAXA's SSPS's Operational View. Source: Nippon Electric Glass (2022).

Xidian University in China, assumed to be heavily associated with their government, has also recently announced a successful test of SBSP "technologies such as high-efficiency light concentrating and photoelectric conversion, microwave conversion, microwave emission and waveform optimization, microwave beam pointing measurement and control, microwave reception and rectification, and smart mechanical structure design"

(Proctor 2022, Introduction). This advanced test of the end-to-end process from tracking the sun to microwave reception and rectification is the most recent developments for SBSP at the time of this writing. The research team has advertised as early as 2028 to have a solar power plant in space, accelerating their previous timeline from 2030. China's aggressive efforts will most certainly have a dual use case for military and civil applications.

C. ELECTRICAL POWER FOR MILITARY OPERATIONS

Electrical power is a commodity and essential for modern military operations. In its absence, all operations, ranging from peacetime to conflict, are severely impacted and crucial systems are rendered disabled. In this day and age, all manner of systems at the tactical edge are reliant on dependable electrical power and range from command and control (C2) functions to hot water heaters. Figure 6 shows the total energy consumption for the DOD in 2021 by fuel type, with the reliance on jet fuel, among other fossil fuels, on full display. The DOD powers a majority of its operations using Jet Propellant 8 (JP-8) because of its ability "to operate at relevant environmental extremes, all the while providing excellent power quality and high reliability" (Jaffe et al. 2019, 23).

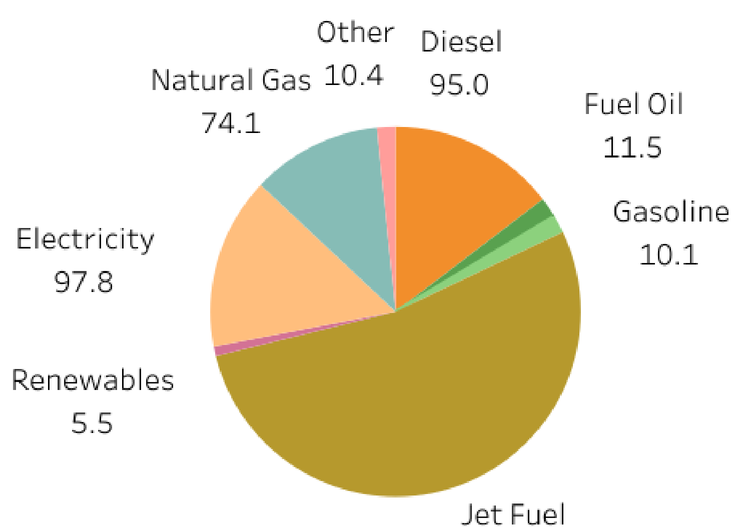

Figure 6. DOD Total Energy Consumption by Fuel Type (Trillion BTU). Source: Department of Energy (2022).

When considering the needs of FOBs, there is a spectrum of power generation, distribution, and transformation that covers tactical power, prime power, and utility power (Department of the Army [DA], 2018, 1–3). Table 1lists the differences in categories, and SBSP could fulfill the roles of each one. However, when considering the practicalities of receiving station requirements such as the area required, maximization of SPS utility, and mission power demands, prime power will be the sort applied in this thesis.

Table 1. Electrical Power Source Levels. Source: DA (2018, 1–3).

Power Level	**Tactical (including individual)**	**Prime Power**	**Utility**
Source output	≤ 500 kilowatts	> 500 kilowatts	Nation-dependent
Distribution	Up to 600 volts (low-voltage)	601 volts – 69,000 volts (medium-voltage)	Up to 230,000 volts (low- to high-voltage)
Expected Duration	Initial (including organic) (up to 6 months)	Temporary or Semipermanent (up to 10 years)	Enduring
Responsibility	Unit	249th Engineer Battalion, U.S. Navy Mobile Utilities Support Equipment, Prime Base Expeditionary Engineering Force, Contract	United States Army Corps of Engineers contract

Note: Voltage here is measured in volts alternating current, or VAC.

The "delineating characteristic between tactical and prime power [for planners] is the level of voltage produced" (DA 2018, 2–1), but when considering the potential for power beaming, the typical demand of FOBs measured in kilowatts produced by a SPS fits more within the realm of prime power. "Prime power sources [also] use transformers to step down medium voltage to lower voltage for equipment usage" (DA, 2018, 2–1); tactical power does not. With a directional beam, the as-needed basis for power beaming really fills in the gap between tactical and utility power, fulfilling prime power's general definition. SBSP's potential utility is most at home here due to its versatility.

Situational changes may arise whereby a military operation transitions to a longer-term solution. When transitioning from tactical power generation to SBSP or co-mingling hybrid solutions, cost savings and improved fuel use efficiency naturally occurs. To ensure continuous sources of prime power, receiving stations would need to have a form of redundancy and resiliency so that maintenance on one or components of a receiving station could be conducted with minimal impact to operations.

III. SPACE-BASED SOLAR POWER SYSTEM ANALYSIS

This chapter presents the results of the SBSP systems analysis conducted in this thesis research. The chapter begins with the identification of potential military applications of SBSP. The next section identifies stakeholders and describes their needs relating to a future SBSP system. Next, the chapter presents SBSP system requirements based on the FOB, which has the highest potential for SBSP utility. Following requirements, the next section presents the SBSP conceptual design and architecture. The last section introduces three concepts of operation for a future SBSP system.

A. MILITARY APPLICATIONS

Identifying the expected sets of operational scenarios and associated capabilities, behaviors, and responses of the SBSP system across its life cycle helps identify requirements that may be overlooked [International Council of Systems Engineering (INCOSE) 2015, 54]. This thesis will explore how a SBSP system could simplify the logistical complications associated with fuel resupplies for forward-deployed forces, expand the energy architecture available to the DOD, and encourage the use of autonomous systems.

Some initial analyses were previously done that puts into perspective the variety of military operations scenarios listed in Table 2, clearly showing that even in 2010 there is value proposition of a SBSP system, though some estimates will need to be updated to account for technology advances and increased global interest since then.

Table 2. Military Operations Scenarios Summary. Source: Jaffe (2010, 587).

Military Operations Scenarios	Rationale for SBSP	Feasibility		Notes	Earliest Operational Capability	Rough Magnitude Cost
		Technical	Economic			
Forward Operating Base power	Reduce fuel convoys	Possible	Possible	Probably best SBSP defense app	>5 years	$10B+
Provide power to a ship or other large seaborne platform	Refuel from space	Possible	Possible	Almost certainly requires lasers and high power densities	>5 years	$10B+
Bistatic radar illuminator	Improve imaging	Possible	Possible	Feasible but expensive	>5 years	$10B+
Provide power to a remote location for synthfuel production	Reduce infrastructure	Possible	Possible	Requires transportation architecture that consumes synthfuel	>5 years	$10B+
Power to individual end users	Reduce battery mass	Unlikely	Unlikely	Power inefficient, severe beam control & safety challenges	>10 years	?
Power for distributed sensor networks	Cover large area	Possible	Unlikely	Power inefficient	>5 years	$10B+
Space solar power to non-terrestrial targets						
Satellite to satellite power transmission	Fractionate spacecraft	Possible	Possible	Significant technical issues, questionable utility	>2 years	$50M+
Space to UAV for dwell extension	Prolong dwell times	Possible	Possible	*if used in conjunction with FOB power	>5 years	$10B+

Terrestrial wireless power beaming applications apart from SBSP						
Ship to shore power beaming	Increase flexibility	Possible	Possible	Attractive defense application, requires more study	>1 year	$10M+
Ground to UAV for dwell extension	Prolong dwell times	Demonstrated	Possible	May be unnecessary in light of recent UAV tech advances	>1 year	$10M+

FOBs are identified as one of the best DOD applications for SBSP due to their existential nature of supporting "50 to 5,000 personnel for military power projection ahead of primary forces" (Jaffe 2010, 586). Assuming the SPS can be redirected for all sorts of missions and is capable of megawatt power beaming, the SBSP system can accommodate increases in FOB power demands by scaling up the area of the receiving station.

The consideration for individual end-users benefiting from an SBSP system is not a novel one but appears to be impractical given the fractional utility of the available power if transmitted everywhere (Jaffe 2010). This is a departure from powering FOBs because the full power beam would be fractionally utilized by comparison, possibly leaving adversaries aware of such a power beam to take advantage of a U.S. asset. The main attraction for this operational scenario stems from eliminating the need for batteries and the logistical challenges associated with its mass, explosive potential, and degradation from extreme environmental factors. That is not to say that there would not be specific mission sets where SBSP would dramatically improve individual end-users' probability of success, but this will not be explored in this thesis.

B. STAKEHOLDER NEEDS

Defined stakeholders and their needs serve as a reference target for the SBSP system. The needs must be feasible, otherwise a solution cannot be devised. Table 3 takes the data listed in Table 2 and focuses on the FOB as the main stakeholder that stands to benefit from a SBSP system and will be expanded upon from the military applications explored further in this thesis.

Table 3. Stakeholder Needs.

Stakeholder	Role	Energy Needs	Relevant Military Application
Forward Operating Bases	User	• Consistent energy • High power	• Resupply • Architecture • Autonomy
Mobile Forces	User	• Precision pointing • Compact receivers • High reliability • Low power • Safe	• Resupply • Architecture • Autonomy
Sensor Stations	User	• Consistent energy • Wide coverage • Low power	• Architecture • Autonomy
Drone Swarms	User	• Consistent energy • Precision pointing • Low power	• Architecture • Autonomy
Satellite Operations Center	Operator	• Hardened comms • Autonomous	• Autonomy

Even the most rudimentary vision of a SBSP system is poised to satisfy FOB needs. By their very nature, FOBs tend to be remote with the mission "to support a small number of reconnaissance and surveillance teams" (Jaffe 2010, 586). Their power requirements are the highest relative to the other identified stakeholders, but the other potential users would be utilizing only a fraction of the capable power output offered by SBSP. In light of this, FOBs will be the primary stakeholder discussed in this section.

FOBs have unspecified power demands due to their ever-changing number of soldiers, support personnel, visitors, and joint or coalition forces—to include their own revolving door of support. This implies the power demand is not only limited to the additional users, but for the land and air vehicles associated with moving personnel in, around, and out of the area. No matter the number of personnel, basic food, supplies, and ammunition will still need to be delivered without which FOBs would be unsustainable or ineffective. The transportation of these goods is a major consumption of fuel. It is clear that energy for FOBs is a commodity that must be reliable and resilient to enable FOBs to operate to their maximum potential.

FOBs are typically in remote or relatively inaccessible areas where power infrastructure is either non-existent or insufficient to meet its needs. Fuel resupply missions then become necessary and generally require tradeoff studies between armed convoys or air resupply (Jaffe 2010, 586). Therein lies a host of issues related to safety, reliability, and costs. The more treacherous the terrain or more present an operational threat, the more risk involved for loss of life or resupply failure. “Operationally, demands for liquid fuel pull personnel away from the fight to provide convoy protection and assist with distribution” (Bulanow, Charchan, and Tabler 2011, 1). This is a recognized problem that FOBs evaluate to continue their mission.

The additional constraint of limited FOB real estate indicates the need for energy sources to be structurally integrated to optimize their footprint. Generators are the standard energy solution and their relatively small dimensions play a part in their tactical utility. One study team from the U.S. Marine Corps (USMC) Expeditionary Energy Office in 2011 calculated the need for 17,046 solar panels spread amongst 12 systems to equal the same amount of energy generated from generator-powered environmental control units, a significant consumer of energy that provides “heating and cooling to deployed Marine forces and facilities” (Bulanow, Charchan, and Tabler 2011, iii). That many solar panels is simply impractical if dedicated to its own area. Hence, structurally integrated energy solutions are essential.

To aggravate the FOB energy problem further, energy efficiency is not the general mindset of base planners, so the go-to solution is to increase supply to meet increasing demand (Vavrin 2010). This corresponds to additional generators and fuel. Alternative energy solutions like solar have been studied to help, and it has been shown to offset problem with innovative energy storage solutions that increase renewable integration capacity of a system, but the sentiment of throwing more money at the problem still prevails. There has been nothing to supplant the convenience and reliability of generators, and with basic assumptions of 1–3 kW/person at the FOB, generator usage can grow rapidly (Jaffe 2010, 587).

C. REQUIREMENTS ANALYSIS

INCOSE best describes the objective of requirements analysis for a system's initial foray from conceptualization as a means to "provide an understanding of the interactions between the various functions and to obtain a balanced set of requirements based on user objectives" (2015, 60). The SBSP system's goal is to deliver wireless energy to the warfighter reliably and on demand. Though the warfighter encompasses any aspect of the DOD in support of a mission, a thorough examination of user needs at the tactical edge illustrates the efficacy of SBSP and its transformative utility. The initial analysis focuses on energy demands and their fluctuation across the spectrum of military operations.

1. Energy Demand Requirements

When planning "power and energy requirements for the operations and support of deployed base camps" (Vavrin 2010, 3), it is important that one assesses the baseline planning factors that occur at the tactical and operational level. Most of the U.S. tactical units in Afghanistan and Iraq during recent conflicts there would have been prime candidates for real-world information about power demands and production for FOBs in that theater. Unfortunately, yet understandably, the Defense Science Board notes that "power data collection was not seen as a significant mission and as a result, power efficiency was not taken as a measure of importance." (2016). This leaves planners to rely on only a few tactical commands' data to analyze, if any at all.

In order for accurate requirements to be identified, there are some gaps in the available power data that must be mitigated (Paul Tabler et al. 2011, 10). If we categorize FOBs as the most demanding warfighter concept, then all other conceptual and stakeholder needs can be met.

A sample of demand requirements that are commonly used for planning by the U.S. Army Corps of Engineers is summarized in Table 4. What is notable is how varied the demand estimation is. It is important to understand that the reference numbers are based on the number of soldiers for the operation. Some other factors that wildly affect the demand requirement are high-power systems like anti-terrorism / force protection (AT/FP) equipment, hot water heaters, soldier support systems to include dining facilities, and even support personnel that exceeds the Soldier population (e.g., contractors, coalition service members, local vendors, Morale, Welfare, and Recreation (MWR) programs, and other Government agencies).

Table 4. Power Planning Factor. Source: Vavrin (2010, 4).

Reference[a]	kW per Person	Company (150)(kW)	Battalion (600)(kW)	Brigade (3,500)(kW)
CENTCOM Sand Book, 2008	0.7	105	420	420
USAREUR Red Book	Not stated by kW/person: Detailed Load Analysis Required			
FM 3-34, 2008	0.7	105	420	2,450
249th ENGR BN Interviews	3.7 kVA	555	2,220	12,950
Air Force Expeditionary Airfield	1.36	-	(550) 750	(3,300) 4,500
"Base in a Box"[b]	1.8	270	1,080	6,300

[a] Does not include field hospitals.

[b] 10 tents (4-ton ECU's) and 2 latrine/shower/sink trailers + pumps; for 100 soldiers

2. Requirement Focus Areas for SBSP System

Many variables are involved in the electric power planning of any military operation (Department of the Army 2018, 5–1). This section identifies and discusses four focus areas that are relevant to developing SBSP system requirements. These four variables help define the requirements and environment for the system, and ultimately "provide the capabilities needed by users and other [DOD] stakeholders" (INCOSE 2015, 52). The best way to ensure success of a SBSP system is to meet those needs and requirements.

a. Energy User Missions

The mission of any operation must be thoroughly understood, along with its anticipated duration. These two factors for mission variability help focus the power planning process, and establish some baseline requirements that dictate power specifications and demand. Shorter mission durations may most effectively be served by tactical power generation, but SBSP may become an option in the trades analysis. If base construction or base occupancy are required for a particular mission, then SBSP becomes a top contender that has benefits outweighing resource investments. It is plain to see that humanitarian assistance or disaster relief missions are longer-term, and requirements can be driven by such characteristics.

b. System Vulnerability to Threats

Given how critical power systems and their distribution networks are to C2, communications, and key weapon systems, understanding the enemy and their capabilities to disrupt any part of the power delivery chain is vital. The DOD should expect enemies to utilize a variety of ground and aerial systems to combat SBSP in a given region. Moreover, the power beam acts as a natural energy resource that could just as well be used by adversaries for similar purposes, reducing advantages gained from SBSP implementation. There are natural threats that could also cause damage to the SBSP system. These include adverse weather to affect the ground-based receivers, natural wear and tear of components, and space debris collisions with the SBSP space subsystem. It is in the recognition of vulnerabilities that base planners can develop mitigation strategies or contingency plans to effectively implement defensive measures for power beaming assets. There are limitations to some mitigations however (i.e., cover, concealment, or shielding), due to the nature of receiving stations.

Nonetheless, it is imperative that requirements recognizing the threat prioritize redundancy and resiliency within the system.

c. Terrain Effects

The power output of generators "decreases by 3.5% per 1,000 feet above 4,000 feet" (DA 2018, 5–1), which can be negated by SBSP. This effectively allows receiving stations to be indifferent to altitude effects on power beaming, aside from inefficiencies of carrying away waste heat with thinner air which could impact operating temperatures. For SBSP to be flexible for a broad mission area, there would need to be an overarching requirement for the power beam to maintain its power link unhindered by coverage with the possibility of clearing or leveling an area before installation.

d. Terrestrial Weather Effects

Terrestrial weather and atmospheric conditions may affect the receiving station equipment that can disrupt the power link. Regions in the tropics or near coastal lines require additional requirement considerations to "prevent corrosion from humidity and salt spray," (DA 2018, 5–1) and other heat-extreme regions like the desert would need to consider heat and dust. There are several published articles that detail operations in climatic conditions applicable to the receiving station equipment.

When considering the power link to the SPS, there will be significant degradation to a laser power transmission than a microwave power transmission by the atmosphere and its conditions. It is imperative that the system requirements address the needs of the stakeholder's terrestrial weather and environment.

3. SBSP System Requirements

The core requirements of the SBSP system are listed in Table 5. The requirements must be validated to ensure they align with stakeholder expectations. Each stakeholder need may have more than one corresponding requirement that satisfies it. This traceability ensures the SBSP system is in fact useful and is designed to meet those needs.

Table 5. SBSP Core Requirements.

Functional Requirements	
1	The SBSP system shall collect solar energy from space
2	The SBSP system shall convert solar DC current into microwaves
3	The SBSP system shall transmit power from space to terrestrial receiving stations
4	The SBSP system shall maneuver power beams to different locations as needed
5	The SBSP system shall be controlled and operated from a centralized authority
6	The SBSP system shall utilize temporary power storage to mitigate interruptions/ disruptions
Performance Requirements	
1	The SPS shall achieve >80% power conversion efficiency in space
2	The power transmission shall be at least 5 MW to satisfy typical FOB requirements
3	The maximum beam intensity shall be limited to 240 W/m^2 for safety
4	The SPS shall have a power to mass ratio of at least 1.0 kW/kg for economy of scale
5	The SBSP system shall provide continuous coverage over a given location
6	The SBSP system shall provide 100% baseload for intended users
7	The SPS shall have a service life of at least 30 years
8	The SBSP system shall be serviceable with replaceable parts
9	The SBSP system shall provide enough power to satisfy monthly baseload demand for remote installations

The functional requirements will provide the operational capability the DOD would need to support their military operations at the tactical edge. They are closely aligned with the needs of FOBs and expeditionary forces deployed at remote locations. The performance requirements are measured in such a way as to elaborate how a function is executed. These are detailed further in the following sections. It is the culmination of these requirements that make a compelling case for SBSP development and adoption in military operations scenarios.

When considering the application of a SBSP system, it is analogous to any primary source of power. As more enduring bases are established, higher level organizations within the DOD are in position to develop and analyze data that would help further studies on SBSP and efficient power distribution in general. The requirements definition done here helped set up a complete and unambiguous baseline that the SBSP architecture can be framed around.

D. CONCEPTUAL SYSTEM DESIGN AND ARCHITECTURE

As discussed, there have been concepts proposed to illustrate the technology since the SELENE project in 1991. With a pool of diverse options originating over the past three decades, a refined high-level structure of systems can be described to best frame the warfighter's needs at the tactical edge.

1. Reference Architecture

A solid reference architecture weighs the insights gained from requirements analysis and frames them around a design-agnostic structure to provide the flexibility in a follow-on design phase. The reference architecture chosen herein uses the conceptualized perspectives of military operations at the tactical edge to guide its development.

Figure 7 is an inputs, controls, outputs, and mechanisms (ICOM) diagram that shows the fundamental relationships between inputs/outputs, functions, and assets. The ICOM sections are identified by the side of the root box, starting with the inputs from the left going into the SPBS system block, clockwise around with controls coming in from the top, outputs going out from the right, and mechanisms coming in from the bottom.

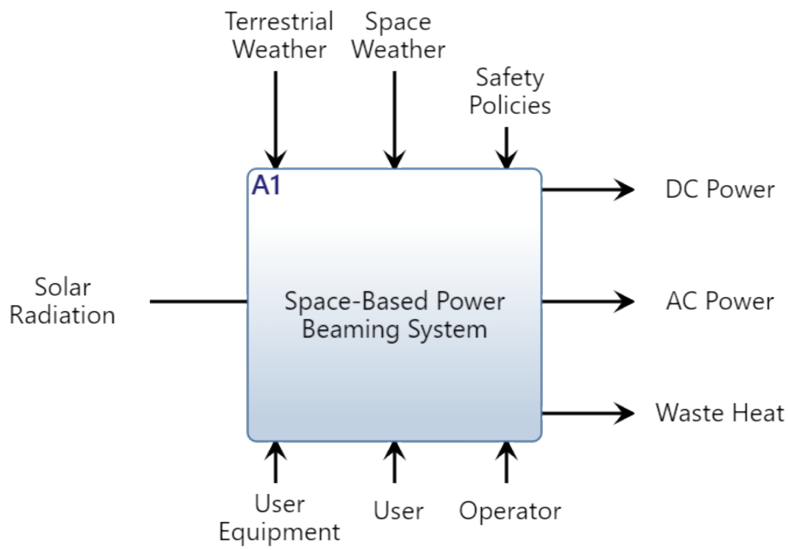

Figure 7. SBSP Input/Output Diagram

The sole input is solar radiation, which is the clean power source from the sun, which effectively acts as an unlimited energy supply for the entire lifetime of the system. To reduce complications, the reference architecture bounds its solar collection in space to avoid terrestrial unpredictability, like diurnal cycles, atmospheric attenuations, and weather effects (Jaffe 2013, 1). A SPS is key to maximizing efficiency.

Terrestrial effects do act as a control factor for the actual power transmission and receiving station due to the nature of an earthbound tactical edge environment. Space weather is a control factor for the SPS as well, with significant effects on the receiving station (and end-user equipment) in a devastating but low-probability solar storm. Safety policies also dictate the type of power transmission and associated controls therein to ensure safety for humans, equipment, and the environment.

AC/DC power is the key output that will be distributed to meet the energy demands at the tactical edge. Waste heat is generated from solar collection and the rectenna and is a natural byproduct of the system. Repurposing this waste heat may be achievable in the future, but will not be explored in this thesis.

The mechanisms taken into account for the system are the physical entities affecting the system in a deliberate way. User equipment varies and can be supplied either directly or indirectly through a power distribution system. Autonomous systems interact with the system on their own accord via their rectennas and can directly benefit from the power delivery. Operators control the system by steering an individual SPS or full constellation to support mission requirements.

With these considerations in mind, the reference architecture decomposes the SBPS system into two parts: the SPS and the Receiving Station. These components fulfill the activities listed in the functional hierarchy diagram shown in Figure 8 below. The activities stemming directly from the metafunction are the minimum functions needed to complete the SBSP system.

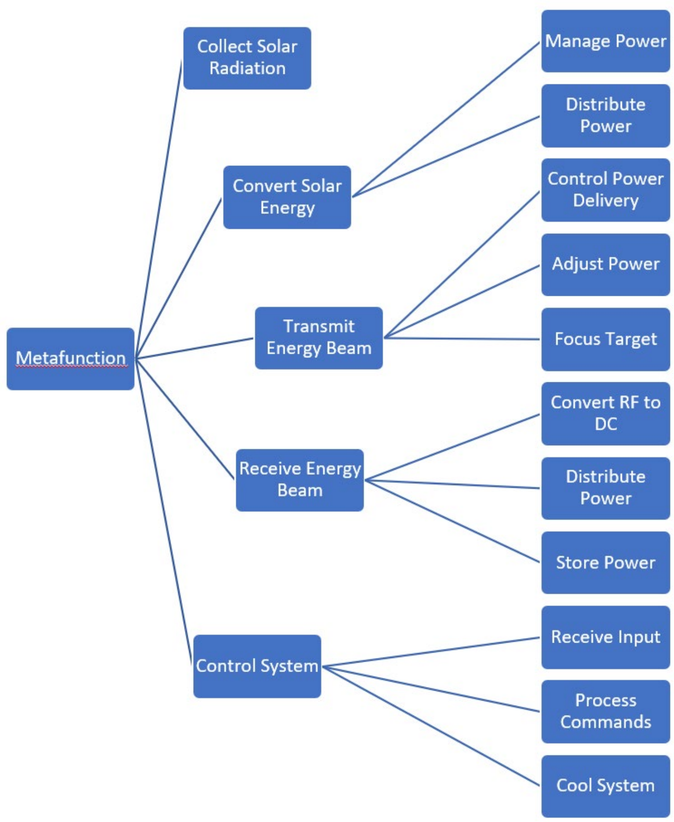

Figure 8. Functional Hierarchy Diagram

2. Solar Power Satellite

There are two basic architectures proposed in the past that encompass the main functions of solar "collection, DC to RF conversion, and power transmission" to Earth (National Security Space Office 2007, 7): a SPS in Earth orbit or a lunar-based system on the surface of the Moon. It has been demonstrated to be feasible to assemble, integrate, and implement a space-based solar power system than a lunar-based one at component or sub-component levels. The International Space Station (ISS) is the most obvious success story. Conversely, no lunar-based demonstrations have been conducted to promote any sort of SBSP feasibility.

When considering an architecture for a space-based SPS, launch costs and frequency both coupled with space structure assembly are significant hurdles to overcome. The technologies associated with these are maturing operationally or still in their nascent stages. One of the earliest SPS concepts was done by the Solar High Study Group by designing a 5.8 GHz derivative of the original 1978 DOE/NASA SPS reference system (Jaffe 2013, 8). Figure 9 shows this SPS concept doing two disparate functions with their respective parts: solar collection by the photovoltaic (PV) panels and power transmission by the transmit antenna. The sheer surface area of the PV panels alone complicates the launch requirements, and that disregards the 800 m transmit antenna.

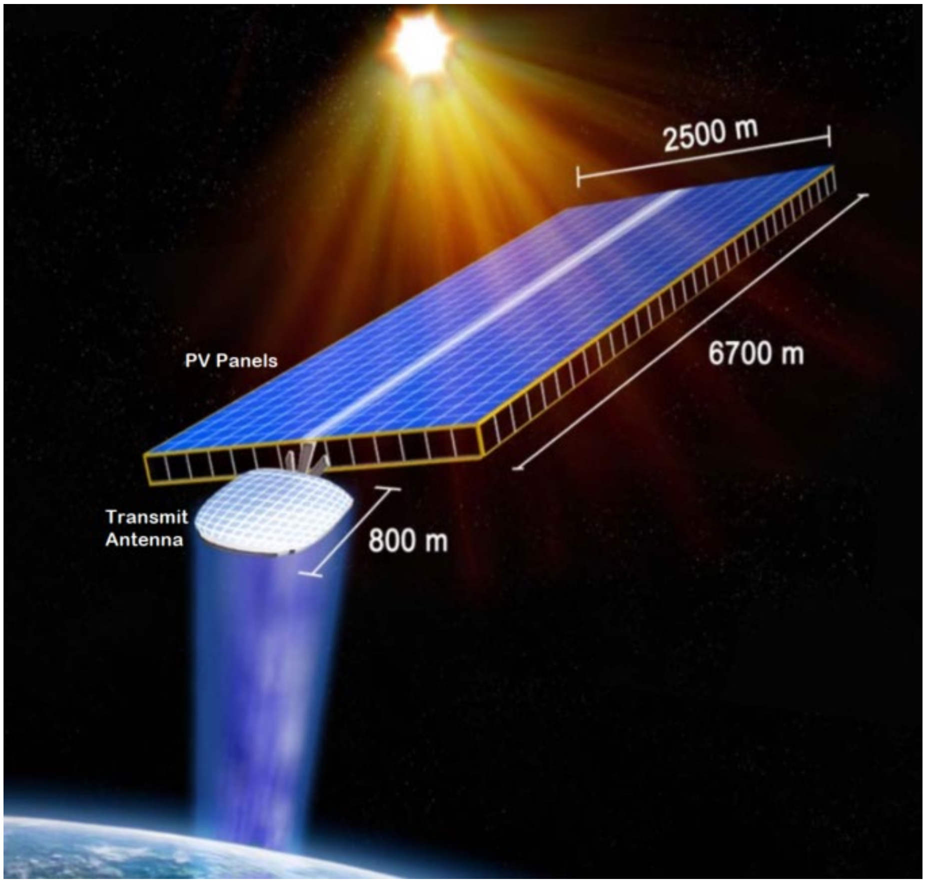

Figure 9. Solar High Study Group's DOE/NASA Reference System. Source: Jaffe (2013).

A limiting factor for the mass of a single SPS can be summarized best by the NRL's assessment which constrains the mass to 555 metric tons (NRL 2019, 14). The motivation in this figure is to limit the funding costs in launch to 25% of the estimated $10B for initial implementation, but now equates to ~70% using updated costs from current launch vehicle pricing; a $24B budget would be needed to maintain a launch cost of 25%. Fortunately, with the advent of reusable rockets like SpaceX's Falcon Heavy and upcoming Blue Origin's New Glenn, launch costs can be expected to be reduced over time. Since Falcon Heavy is operational, we can base our launch costs to geostationary transfer orbit (GTO) around its specifications with reusability in 2022: $97M per 8 metric tons per launch. That gives us a figure hovering around 70 launches totaling $6.7B. This figure can only be further improved by SpaceX's successor launch vehicle, Starship, which is planning to have a larger thrust and therefore a larger payload capability.

In addition to the SPS's overall size and mass exceeding our current launch capability, there is another enabling technology needed to realize the SPSB system in development by NASA as in-space assembly (iSA). The SPS must be designed into modules so its delivery into space can be done over a series of launches, and ultimately built by using robots or astronauts via iSA. This lends itself to abnormally large physical space requirements to maximize solar collection. Though this allows for the design and manufacturing of more complex parts while structural trusses or panels undergo iSA, this does contribute to the overall implementation timeline.

Shown in Figure 10 is another concept that takes the "Reference System" by bringing the PV panels closer to the transmit antenna but introduces concentrating mirrors to focus the sunlight. This results into a more complex structure that requires more moving parts to keep the mirrors pointed, muddling an already exhaustive iSA.

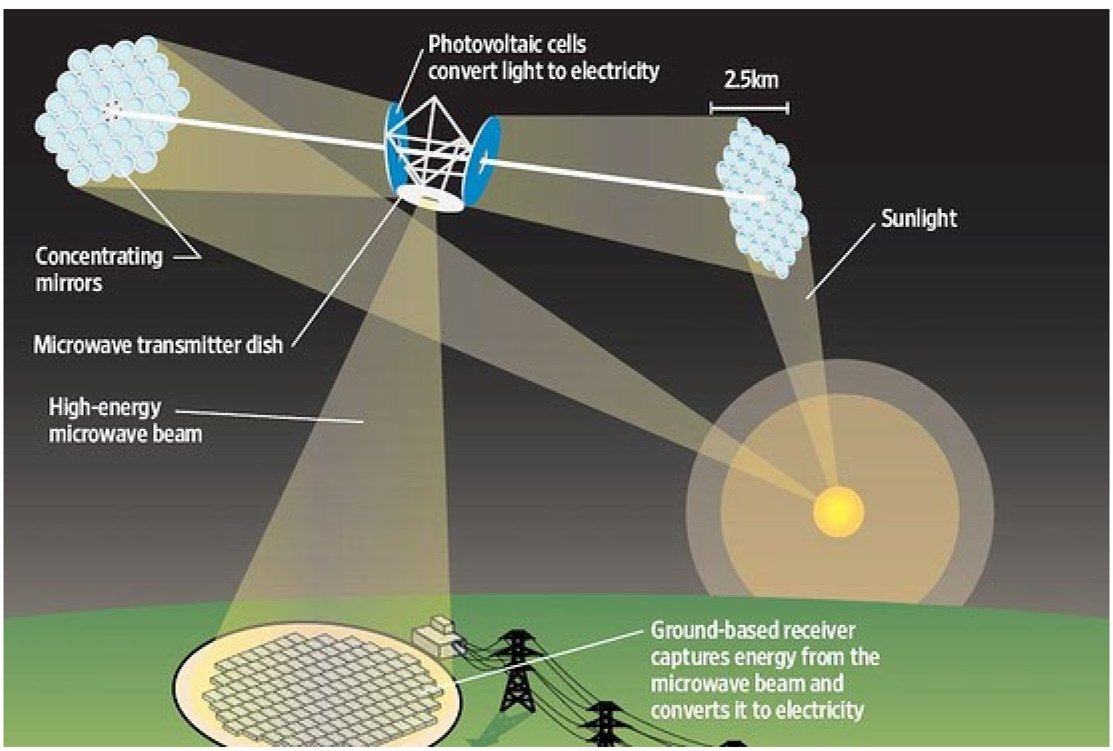

Figure 10. SPS Concept Using Concentrating Mirrors. Source: Torrey (2009).

There are some considerations for the SPS design if placed in the LEO environment. This would require a constellation to provide sufficient coverage of target areas and a significant cost increase associated with the manufacturing, launch, and iSA of multiple SPS's. Another notable factor is the durability for each SPS to function in the face of LEO environmental threats like micrometeoroids, space debris, and massive thermal cycling. This entire constellation will be further stressed because each orbit around the Earth at LEO is approximately 90 minutes (de Groh, Banks, and Smith 1995, 6). The high heat from the sunlight followed by cooling in the Earth's shadow are considerable temperature fluctuations that must be accounted for in the materials used; otherwise, microcracking and delamination of coatings could lead to a host of issues like ultraviolet radiation, atomic oxygen, and contamination. If one SPS malfunctions, is rendered disabled, or produces debris in LEO, then it leaves a gap in functionality for a target receiving station as well as compromising the rest of the constellation.

Once the SPS is in its desired orbit, there are some different designs that meet the referenced architecture that have been proposed in the past. Figure 11 illustrates a historical concept that show a physically separated solar collection and power transmission components connected by a truss. More recent developments like the demonstrations underwent by NRL in their PRAM module consolidate the solar collection, DC-to-RF conversion, and microwave transmission functions into a single tile module, allowing for a more compact design that may simplify the iSA and serviceability. This could lead to a more compelling SPS that is modular, uniform, and more resilient to part failures.

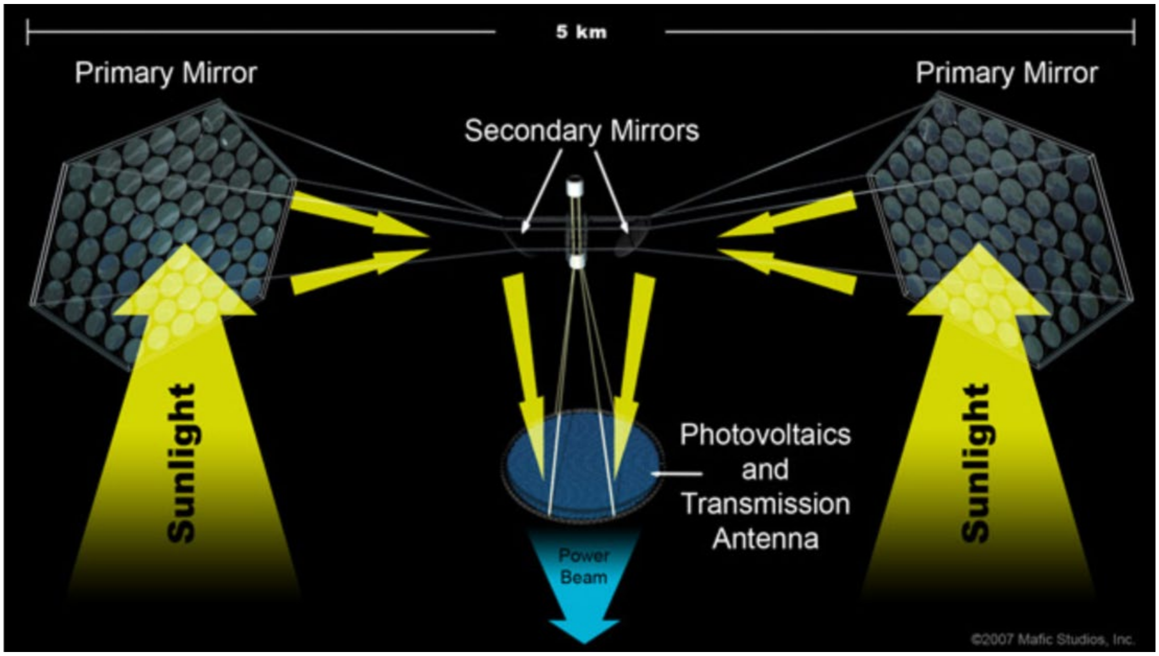

Figure 11. Modular Symmetric Concentrator Concept. Source: NSSO (2007, 8).

3. Receiving Station

The Receiving Station must be able to accept the power transmission from the SPS and distribute it to the end-user based on demands. The Receiving Station architecture will be composed of rectifying antennas, AKA rectennas, whereby RF signals are received and converted into DC power. The energy distribution thereafter can utilize batteries for storage or feed directly into the needs of the end-users, which are technologies and processes relatively well understood and will not be a focus for this thesis.

Figure 12 shows a thin-film etched-circuit rectenna that was designed and evaluated for its power handling capability with its intended application to microwave-powered high-altitude aircraft (Brown and Triner 1984). Because of its thoughtful design for atmospheric platforms and power transmission in space, it must be carefully considered for military purposes whereby terrestrial energy needed measures in the GW. Dependent on power level densities, these rectennas can achieve an overall RF-to-DC conversion efficiency of up to 91%, which would be a boon for power-hungry requirements. However, to account for the IEEE safety limit for controlled areas from 3 GHz to 300 GHz, which averages to a power density of 100 W/m^2, a thin-film etched-circuit rectenna would be approximately 120 m and weigh about 250 kg (NRL 2019, 17). That is about the size of a football field.

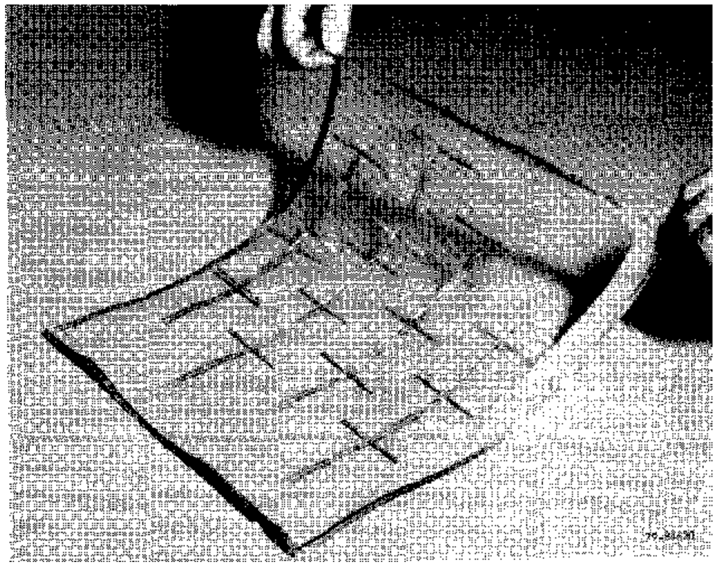

Figure 12. Thin-Film Etched-Circuit Rectenna. Source: Brown and Triner (1982).

The type of flexibility demonstrated by Brown and Triner allows for unconventional transportation methods for these receivers to accommodate a wide array of missions. They could be packed for mobility via shipping containers by sea, standard pallet system by existing aircraft, or even by trucks or trailers. There also are a number of deployment solutions for traditional PV solar panels today that can be utilized for thin film rectennas. Figure 13 shows a rapid deployment solution by a trailer that rapidly unrolls the panels without the need for solar engineers on-site (IMPO-RF 2022). Alternative solutions can range from airlift by heavy-lift helicopters, shipping containers, or even autonomous deployment by robots. Additionally, the array of rectennas could be installed upon or integrated with buildings, tents, or other structures for further flexibility and rigidity (NRL 2019, 18).

Figure 13. Existing Mobile Deployment Solution for Solar Panels, AKA Rapid Roll "T" by RenovaGen. Source: IMPO-RF (2022).

Much like traditional terrestrial solar arrays, the Receiving Station would need to share similar prerequisites to establish an efficient power beaming link. A level surface or terrain would help in not only the deployment but also to minimize any coverage affecting the rectenna's efficiency. If that is not feasible, supporting structures would need to be considered. The nature of thin materials that comprise the proposed rectennas has challenges associated with its deployment and overall management. Wind, foliage, ice, dust, and other materials that tend to attenuate microwave signals must be avoided or obviated to maximize the power beaming link's potential. However, it has been confirmed that wave attenuation is negligible for frequencies below 30 GHz and even for storms with more visibility more than 0.02 km (Chen and Ku 2012). This should be studied further when devising a comprehensive solution.

4. Command and Control

C2 is considered a critical part for operations and maintenance for all satellite systems and the SBSP system is no exception. It must be a two-way communication link with centralized management rooted at a Satellite Operations Center (SOC). It is from here where commands for specific tasks are uplinked, with the chief among them providing coordinates to point the beam in the desired location. Ancillary commands would encompass those for satellite control related to maintenance, collision avoidance (if not automated), and pause in operations or decommissioning. The basic C2 architecture for the SPS also requires uninterrupted status updates of Telemetry, Tracking, and Commanding (TT&C) for health monitoring, and the C2 signal paths can be seen in Figure 14

The "two basic approaches [for] C2 links [either uses] direct ground access [or] relays. In the relay operation, [an uplink] an uplink signal is sent from a ground station to a relay satellite, which then transmits a forward link to either another relay, or to the destination satellite. The return link from the destination is received by the relay, which then transmits the signal to the ground station via the downlink" (Butler 2018, 1). Whichever pathway the signals take, the initiator and TT&C consumer is always the SOC.

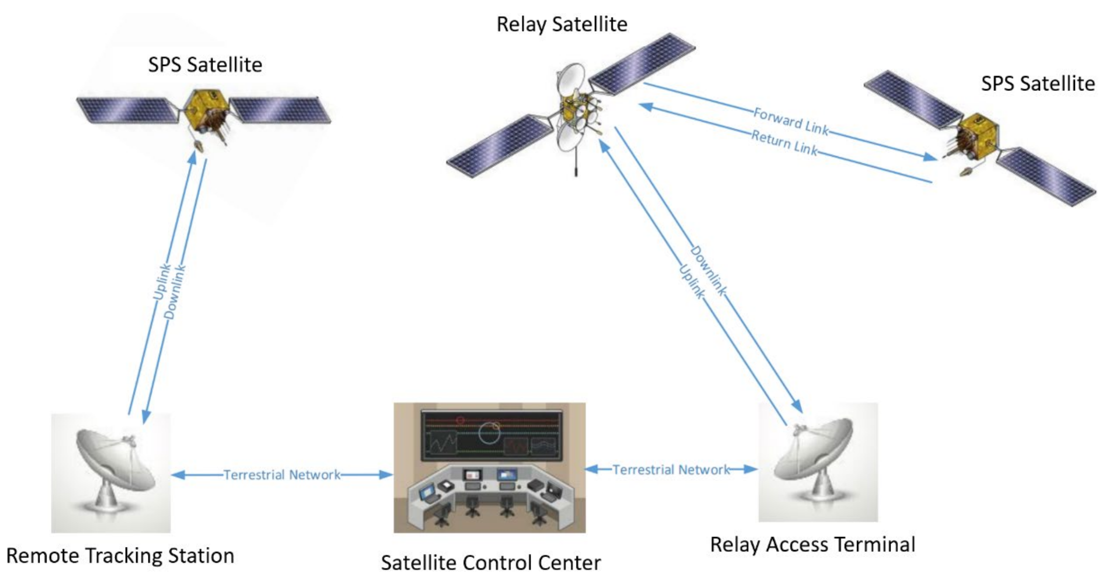

Figure 14. SBSP SPS C2 Architecture. Adapted from Butler (2018).

This architecture is standard and considered old, basic technology as of 2018 in terms of satellite C2 capability. If the SBSP system were to support both a direct link and relay modes of operation, Butler rightly infers there would be redundancy in the multiple access methods (2018) to reach the SPS. There has been research in utilizing rectenna control stations coupled with a SOC to build a decentralized communication architecture, but was determined as a low priority effort that could be delayed at a later time without impact to SPS development (Raytheon Company 1979, 5–7). This same research also proposed a manned SPS where up to 50 personnel could help operate and maintain the power beams. In light of research and advancements in autonomous systems, the functions of an SPS can be achieved autonomously negating the need for complex C2 and other superfluous communications systems that would accommodate resident staff.

A decoupled link from the SOC is the pilot beam, which is the primary C2 link from the rectenna to the SPS. The purpose of the pilot beam would be to orient the SPS microwave power beam currently to the receiving site. JAXA Researchers have proposed a system in which spread-spectrum pilot signals are used with phase-detection circuits so that a single antenna on the SPS can be used for power transmission and pilot-signal reception (Hashimoto et al. 2004, 31). This effectively utilizes a single frequency for SBSP operation, eliminating the need for another frequency spectrum and the difficulties associated with obtaining spectrum allocation approval. Figure 15 shows the pilot signal being transmitted from the rectenna's center allowing for accurate beam control and reducing the reliance on mechanical attitude control.

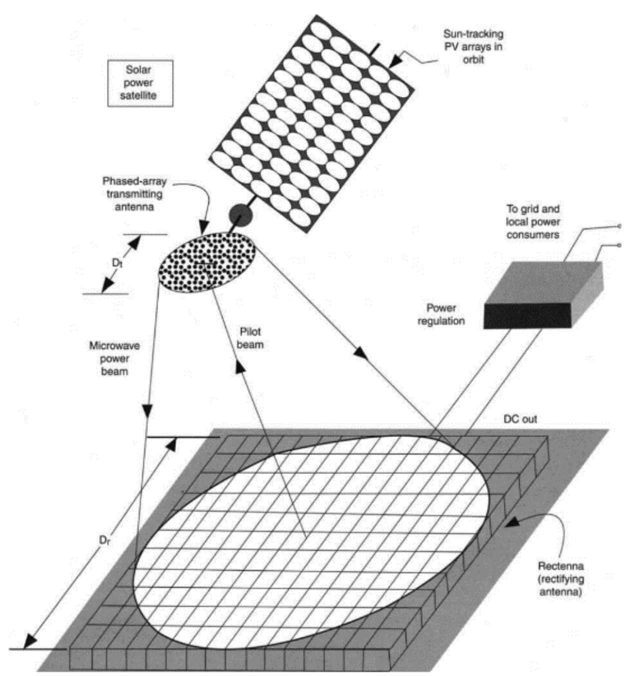

Figure 15. Rectenna's Pilot Beam Transmission. Source: Caldeira and Hoffert (2004).

5. System Security

Satellites were once considered relatively safe from adversarial intervention in the past, however vulnerabilities seem to manifest with every couple years as there are increasingly displays of "intent and means to compromise and cripple space capabilities" (Butler 2018, 1). Some recognized vulnerabilities for the SBSP system arise from anti-satellite (ASAT) weapons and C2 link exploitation, to include passive and active methods.

Direct ascent ASAT (DA-ASAT) capabilities involve ground-, air-, or sea-launched rockets on a ballistic trajectory up into space to target space-based assets. The proposed SBSP system would be positioned in deep space at GEO, but there are design options for a LEO constellation. LEO DA-ASAT weapons are likely mature and potentially operationally fielded on mobile launchers. This is a major international concern because the destruction of any one satellite passing overhead could create debris for any LEO-based asset, and create further problems for future launches. GEO DA-ASAT are actively being pursued by China as a counterspace measures, but likely in the experimental or development phase (Weedan 2021).

There are no known ASAT countermeasures at this time, but detection has been "estimated to be about 5–15 minutes for LEO and several hours for GEO" (Weedan 2021, 3). This threat must be followed closely to develop mitigation strategies aboard the SPS or external to the system, but SBSP is not unique in this vulnerability. It should be noted that a moratorium on DA-ASAT missile tests was issued by the U.S. in April 2022 in an attempt to "prevent an arms race in outer space" (Panda and Silverstein 2022), but it remains to be seen in how countries like Russia and China will respond. Whatever the case, ASAT capabilities could disable the SBSP system.

Another attack vector for the SBSP system is not from the power beam itself, but rather the C2 link. It is standard practice to encrypt data streams to provide "secrecy and some degree of authentication, [but] waveforms themselves do not in any way hide the traffic flow" (Butler 2018, 2). This allows for signals to be easily identifiable when examined, allowing external observers to infer things about the SBSP system. Standard cryptography can waylay any unauthorized commanding of the SPS, but because frequencies and modulation are not difficult to reverse-engineer from years of observation, bogus signals could be produced to prevent legitimate commanding from the SOC. This interference, AKA jamming, would prevent beam control and more egregiously, system failure. This susceptibility to interference can be mitigated by implementing spread spectrum techniques that also enhance covertness, which decreases legitimate signal detection. Butler, in his conference paper to enhance satellite resiliency, outlines frequency hopping, direct sequencing, or some combination of those techniques to implement spread spectrum and effectively harden the C2 link. These measures are typically applied to general communications, but not normally to C2 links. The SBSP system should build upon the concepts and principles therein for increased system security.

E. CONCEPT OF OPERATIONS ANALYSIS

There are SBSP use cases from which the DOD would benefit greatly to help reduce costs, increase safety, and offer extensibility for a variety of missions. The military use cases that are most apparent in reaping the benefits of the SBSP system are shown in Figure 16, which is an operational view of the three applications discussed in this thesis: (1) to drastically reduce risks associated with generator fuel resupply, (2) to provide a comparable complementary or alternative power solution, and (3) to progenerate concepts and plans for more autonomous aspects in future operations.

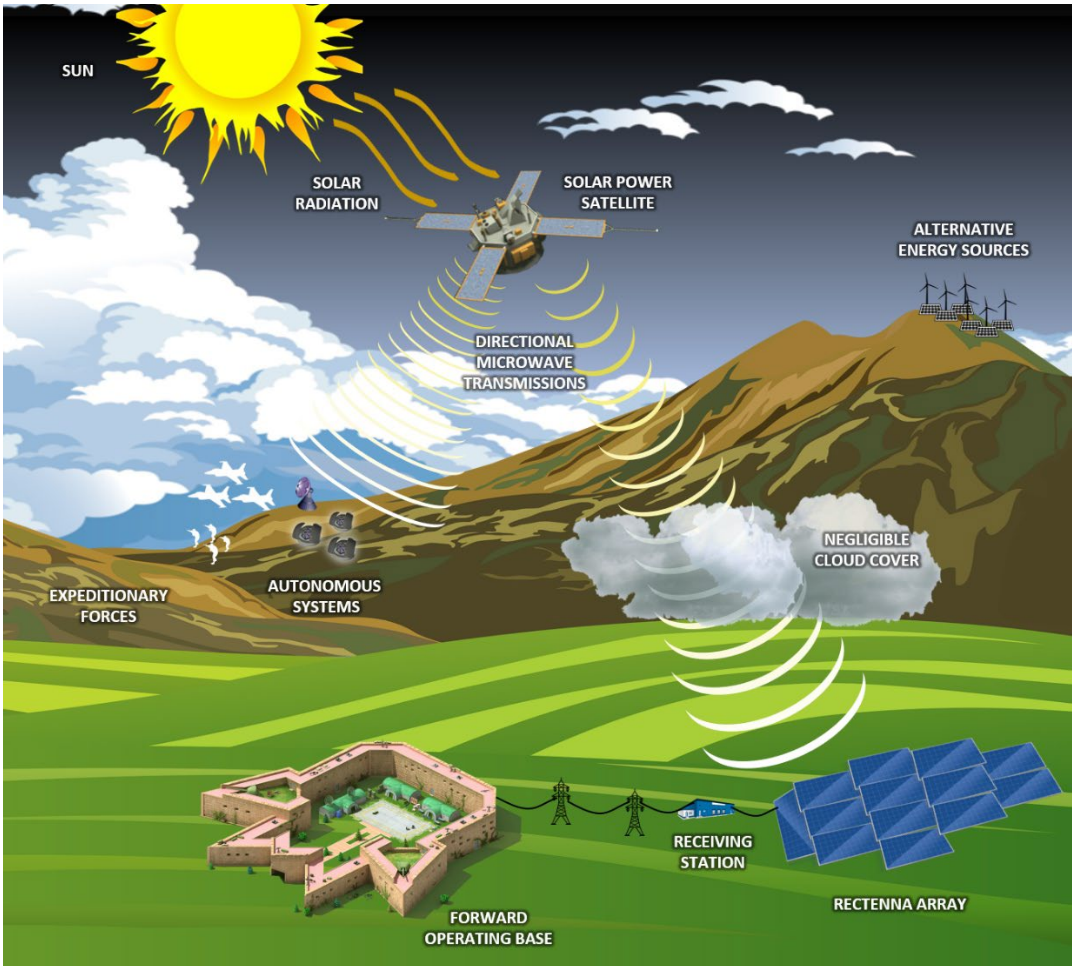

Figure 16. Operational View of a SBSP System

1. Reduction of Energy Logistics

The delivery of energy to FOBs usually entails the delivery of generator fuel. There was field data collected from 2009 related to a USMC Afghanistan study that showed "for every gallon of generator fuel used, it took seven gallons to transport it" (Vavrin 2010, 8). Therein lies the implication that overall operational costs can be reduced by also reducing the need for transporting fuel to a site. Furthermore, when data suggests that "fuel consumption for the typical plant ranges from 40 to 220 gallons per hour" (Vavrin 2010, 15), then it is apparent that the energy required in logistics alone is something that would benefit FOB costs if abated.

Organizations studying the logistics of resupply state that "beyond the high dollar cost of delivering fuel to the battlefield, it is important to [also] measure the operational drawbacks associated with dedicating manpower and equipment assets to resupply, including [the] receiving and [storage] materials, and the associated risks which include injuries and loss of life" (Defense Science Board 2016, 8). Reduction in logistical activity related to energy resupply can improve the overall force protection for the warfighter, and additionally free up their time and assets to improve warfighting capabilities. There is the issue of problematic terrain (e.g., desert, jungle, mountain, arctic, etc.), or terrain features (e.g., cliffs, ridges, depressions, etc.), for remote installations or FOBs that may not be conducive to effortless energy resupply. These types of complications pose significant risks to the logistical team and their assets, and may affect the resupply mission altogether. The worse case scenario is the loss of life and equipment, with a resulting failed resupply.

SBSP does not require any sort of refueling and overcomes all risks associated with resupply by fully negating it.

2. Increase of Energy Architecture Flexibility

The 2009 Afghanistan study mentioned by Vavrin also determined that due to the high operation tempo (OPTEMPO), which summarizes the rate of a unit's activity, renewable energy in that type of environment and in the near-term would "only provide a fraction of the total energy required" (2010, 9). This study is over a decade old, and technological advances and recent demonstrations showcase otherwise, and that the incorporation of renewable energy at the tactical edge has some merit.

The inclusion of a SBSP system to the pool of energy architectures for DOD investment increases the flexibility of power planning at the tactical edge. Mature alternatives to fossil fuels shift the paradigm in how operations power the warfighter. Any displacement of the proliferated incumbent technologies requires compelling motivation and sufficiently developed replacements (NRL 2019, 29), so the dividends from advancing a SBSP system are credibly significant. Sophisticated trade studies may show that a SBSP system would be constrained by missions with relatively small energy demands or areas with little to no space for receivers, but essential otherwise. Even hybrid power solutions that make use of a SBSP system will find savings and a much favorable outcome.

3. Ushering of Autonomous Systems

As the warfighter evolves and explores the use of uncrewed autonomous assets, the SBSP power beaming link further compels the mission designers at the tactical edge to consider not only staffed users, but autonomous users as well. "Although a traditional [FOB] has needs besides energy, including water, food, and ammunition, a prospective future installation or group of autonomous systems might not have such needs" (Jaffe et al. 2019, 8). The transition to autonomous systems gives rise to even more dependence on reliable and constant energy delivery.

A SBSP system can provide the reliability and consistency sought after by power-hungry operations. Consider scenarios in the future in which an installation, mobile group, or expeditionary force heavily dependent upon autonomous assets that relies on electricity for all aspects of their operation, to include mobility, on-board processing, and communications; advancements may also incorporate directed energy weaponry into these assets whereby the electrical load for each asset would be even higher. This scope can be expanded further to a decentralized system or fleet of autonomous vehicles. SBSP could then present a near-total means of resupply that exceeds today's limitations of available energy in a given operational environment. The space-based powering of autonomous systems is a net positive for the DOD.

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IV. ASSESSMENT OF SPACE-BASED SOLAR POWER BENEFITS AND CHALLENGES

There are significant SBSP benefits and challenges that are worthy of further investigation. Though SBSP could serve as the paradigm shift that enhances DOD operations and provides more capability, there are challenges that must be overcome to fully reap the benefits.

A. ANALYSIS OF BENEFITS

Some analyses portray the SBSP system as a competing technology, but the maximum benefit in the short-term can be realized when it is viewed as a complimentary system to the available options that enable the warfighter at the tactical edge. When viewed as a long-term solution, SBSP does fill in gaps for longevity and reliability that is not sustainable with traditional fossil fuels. The main appeal is moving energy from where it is cheap and accessible to places where it is difficult to come by.

1. Net Zero

Net Zero, though international, is most certainly a U.S. goal for mitigating global warming by 2050 and was born from the understanding of climate change as concerns about its impacts swell. The U.S. is partnering with countries around the world to accelerate global energy system decarbonization by increasing the speed and scale of transitions to net zero energy systems (National Renewable Energy Laboratory 2022). This commitment holds little water if the U.S. fails to peer inwards at its own energy usage and rein in the elephant in the room. Figure 17 shows the DOD owning the lion’s share of energy consumption making it patently clear how intense their demand should be for a new energy solution.

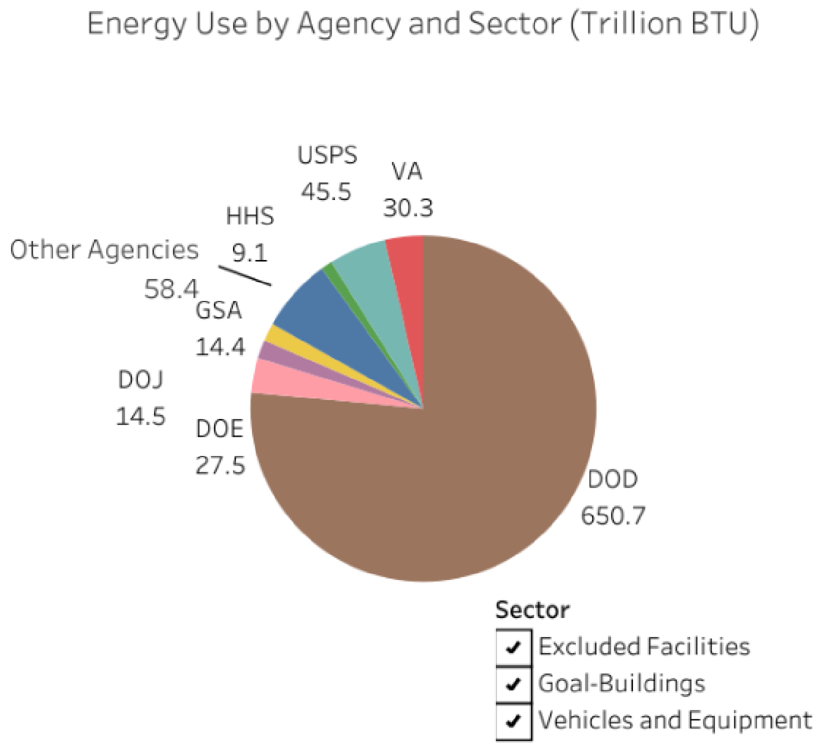

Figure 17. Energy Use of DOD in Trillion BTUs. Source: Department of Energy (2022).

An SBSP system is carbon-neutral—from the solar collection to the power distribution—and avoids the creation of new environmental concerns during operation. Though the initial efforts to design, build, and execute will require manufacturing, rocket launches, installation, and other ancillary efforts detracting from Net Zero, this technology ultimately meets the intent and could accelerate the goal on a global scale, all the while drastically reducing the largest contributing agencies' dependence on fossil fuels.

Energy technology is of profound importance for the DOD—and to a broader extent, human civilization—in order to further U.S. interests across nations and expand U.S. presence beyond.

2. Synergy with Terrestrial Energy

The natural precursor to the SBSP system is terrestrial solar power. It has become increasingly prevalent to supplement fuel-consuming generators with solar arrays and batteries to reduce fuel demand, so it stands to reason that SBSP can share this load. Any SBSP requirements like low cost, high efficiency, and high production of solar arrays would naturally improve terrestrial solar power and attract its adoption in both civilian and military markets. It is imperative that technology maturation in terrestrial solar power continues to move forward and exponentially so, such that SBSP may be realized sooner.

Terrestrial solar power has shown promise with "successful demonstrations in remote Marine Corps outposts, on dismounted soldiers, for sensors, and on UAVs" (Defense Science Board 2016, 26). There are gaps in its utility that when coupled with SBSP, enhances the capability of solar power overall. The variability of terrestrial solar energy on a global scale is subject location, season, weather, and time of day. The placement of the SPS "at the Earth-sun L2 Lagrange point [would have] a constant view of the night side of the Earth" (Landis 2000), and a power beam link at or below 3GHz would remove those limiting factors altogether. This effectively upgrades terrestrial solar power's availability to be 24/7, changing solar power's intermittent status to constant.

Furthermore, SBSP receiving stations comprise of rectennas and would need to take up a sizeable portion of land. It is recommended that an analysis of SBSP designs consider how it compliments the terrestrial solar infrastructure that will be "developing [at] a faster scale than the space infrastructure" (Landis 2004, 10). There are enough functional similarities between the terrestrial solar array and rectenna array, such as their receipt of energy from space and conversion into electricity, that an upgrade to rectennas would be relatively trivial to a new installation. There would be no need to allocate or pay for a new site, the distribution infrastructure would already be in place, and with enough technical advances, a solar array can be designed with integral rectennas built in (Landis 2004, 17).

3. Leadership in Power Beaming Technologies

There is an opportunity in which the U.S. can establish its leadership in relevant technology areas, offering prospective benefits beyond defense, "but also for diplomacy, development, and domestic economic growth" (Jaffe 2019, 27). For example, alliances can be strengthened by providing humanitarian aid to those countries that undergo natural disasters. The U.S. can maximize the use of its own land by providing energy to places that have been traditionally difficult to extend power to. A new option in the domestic energy sector can shift markets and provide more opportunities for businesses to grow.

Without more U.S. investment, countries that have heavily invested in developing and maturing SBSP will reap the benefits of relevant technologies. China proposed a SBSP development roadmap to "building a MW-level demonstration by 2030," (Li 2022, 1) which describes a continuous 1 MW power beam transmitted from space to the ground, and then building up to a commercial SBSP by 2050 (Li 2022, 1). Additionally, a team in China expects to have an initial SBSP system by 2028 as part of their Orb-Shape Membrane Energy Gathering Array (OMEGA) that was proposed in 2014, advancing their timeline by 2 years from 2030 (Proctor 2022). If U.S. were to lag behind, there may be dependencies on this technology that would be counter to U.S. interests. The Chinese perspective could be best summarized by Wang Xiji, a Chinese space technology pioneer: "Whoever obtains the technology first could occupy the future energy market. So it's of great strategic importance." (Jaffe 2019, 29).

The next decade will be influential and perhaps monumental for SBSP as key enabling capabilities advance, technological breakthroughs occur, and cutting-edge research presses on. Leaders will emerge that could shape the battlefield as well as global markets, and the U.S. must invest decisively and proactively to maintain its leadership in space science, of which SBSP falls under.

B. ANALYSIS OF CHALLENGES

It is important to note that SBSP is not a staple in operational considerations because it has many challenges that must be addressed.

1. Technological

There are some specific technological challenges spread across the breadth of technology areas that play pivotal parts in realizing a SBSP system.

a. Mass to Power Ratio

The most important metric for the SPS is the specific power or watts per kilogram. The efficiency of the SPS hardware directly improves the specific power and intuitively, the weight of the SPS indirectly improves the specific power. This optimization is key not only for the utility of the power transmission, but for the economic viability in terms of launch costs.

The SBSP system depends on launch vehicles to transport SPS modules and/or components from Earth. Due to the SPS's sheer size, multiple launches will be required. "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" (Jaffe 2019, 27). The launch into space and subsequent orbit is a prominent cost driver in the system, so therein lies the incentive to increase the wattage per kilogram. To exacerbate this challenge, 10 W/kg only accounts for the demonstrated transmission hardware, so there must be a reckoning with the supporting structure, inter-cabling, and PV arrays.

NRL's ongoing PRAM experiment is laying the foundation for how the conversion process from solar to RF plays out in a space-like environment. The data will inform development in this function, but there is more to do to improve the mass-to-power ratio problem. There may be differences between this conversion process on the ground than in space that begs for more investigation so that specific power can be designed for optimality.

b. Unprecedented Area-to-Mass Ratio in Space

Due to the sheer amount of area required for solar collection to reach megawatt levels of power transmission, the SPS requires significant advances in space robotics and iSA. This categorizes space robotics and iSA as key enabling technologies. It has been noted that though mass be kept as minimal "as possible for cost reasons, [this would still] likely result in unprecedented area-to-mass ratio structures" (Jaffe 2019, 28). The largest structure to have been built in space is the ISS, and that required international cooperation and ingenuity over more than two decades-worth of effort—that equated to 40 assembly flights. Trade studies must be undertaken to analyze the necessary modular designs, which consequently results in other challenges like in-space servicing of a bad module, replacement costs, and even thermal control challenges posed on modularity.

The large area-to-mass ratio boasts further challenges in pointing and station-keeping. These ancillary “challenges arise from the influence of the solar wind and from material rigidity and strength limits” (Jaffe 2019, 28). Because the SBSP system must establish a power beaming link for operation, pointing and station-keeping is essential to gain the DOD’s confidence in reliability.

The astronomical community have spurred workshops that pursue detailed engineering assessments of iSA to steer the future direction of space robotic systems development (Thronson et al. 2018), but telescope complexity has been their focus. It is imperative that SBSP inserts itself in future conversations to include large structural requirements. The White House officially released the *In-Space Servicing, Assembly, and Manufacturing National Strategy* in April 2022 that highlights iSA as it relates to space industrialization. It is great that the U.S. recognizes the need for advancement in this field and influencing this sector could very well quicken the SBSP timeline.

2. Economical

The initial investment to realize a SBSP system may not be less than billions of dollars because costs are “driven primarily by the number of launches, in-space transportation into orbit, hardware production, and research and development (Jaffe 2019. 28). This is a hard pill to swallow when mission requirements are currently being met with existing technology. Though simplification of different modules within the SPS may reduce the production and operating costs, as well as shrinking the dimensions and mass of various parts, there is a hefty price tag associated with that research with a timeline that is still not within the near-term horizon.

Furthermore, there is still too much uncertainty in how much the cost of SBSP energy will be compared to alternatives, especially with the current pace of progression. Expeditionary forces typically have high energy cost scenarios that is difficult to forecast, and most of the energy consumption comes from fossil-fuel dependent aircraft and ground vehicles. The shift to electric vehicles may help the fuel reduction, but other factors like battery recharge rates and range could further complicate logistical planning. An implementation of a SBSP system would result in a much more manageable logistical burden related to fuel convoys and a reduction in non-base camp fuel consumption, but no comprehensive analyses could be found that clearly show these results. Ultimately, energy delivered must be generated and transmitted efficiently for economic viability.

3. Political

Electromagnetic spectrum allocation for the DOD is the regulatory responsibility of the National Telecommunications and Information Administration (NTIA). NTIA recognizes the prospects of space solar power being part of the "the next gold rush," (NTIA 2021, 52), but the half sentence related to SBSP is reduced to a mere mention in their most recent report designed to inform policymakers and the public regarding the key roles of U.S. space-based operations. The lack of attention on this technology is certainly a challenge that will require more benefactors to overcome. Without enough proponents, the frequencies likely to be involved with an SBSP system (5.8 GHz, 35 GHz, 94 GHz) may be relegated solely to existing users at military airfields, further complicating a SBSP system designed for remote installations (Jaffe 2019, 29).

There is a single International Telecommunications Union (ITU) report on wireless power transmission (WPT) that was updated in 2021, and it distinguishes the WPT technology as a game-changer. It lists the many global efforts undergone to explore use cases in a wide range of applications via different radio waves, to include wireless charging for electric vehicles, moving/flying targets, buildings, robots, and more. The report touches on SPS microwave frequencies spanning 1–10 GHz, with emphasis on 2.45 GHz and 5.8 GHz (Radiocommunication Sector 2021, 27). SBSP spectrum requirements and candidate frequencies are on the radar of regulatory bodies, but no formal allocation for SBSP has been assigned to an ITU service. This process could take many years so early actions on this front are just as important as the underlying technological R&D.

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V. CONCLUSION

A. SUMMARY OF THESIS RESEARCH

This thesis concludes that the DOD should invest in the underlying technologies of SBSP and take meaningful steps to advance capabilities and realize the SBSP system. It deserves concerted development because the military applications are vast and benefits to military operations at the tactical edge could save money, time, and lives.

Major stakeholders of the DOD were identified to be the military personnel supporting operations from FOBs and expeditionary troops conducting operations at the tip of the spear. Their needs were formed into requirement categories affected by the mission, vulnerability of threats, terrain, and terrestrial weather. The requirements analysis process afforded this thesis an opportunity to review proposed SBSP system architectures in the past and define a government reference architecture that can be used to maximize the solution space. The main functions of the architecture were decomposed to help simplify the focus of the power beaming technology, dividing the segments into space, transport, and ground.

Concepts of operations were explored further to illustrate the vast utility of SBSP. The reduction of energy logistics would mitigate risks for logistics teams and equipment and cut costs for these types of logistical operations. SBSP would broaden the energy architecture of the DOD and allow flexibility in operations planning. Lastly, the availability and improved reliability of energy that SBSP provides would help usher in autonomous systems for the warfighter, reducing the need for troops on the ground.

An assessment of benefits and challenges was conducted. The benefits are meant to inform decisions related to SBSP utility and SBSP's part in fulfilling the U.S.'s obligations to space superiority and carbon neutrality. Numerous challenges were discussed that spanned technological, economical, and political to set the stage on what system architects and developers should look forward to so our understanding of SBSP can continue to evolve.

B. RECOMMENDATIONS FOR FUTURE WORK

Ultimately, the research herein is meant to serve as a baseline for future work. Though SBSP's potential to change the warfighter's landscape is decades away at the current funding levels associated with SBSP development, there are known efforts today that could be undertaken to advance capabilities and keep the U.S. in the running for untapping SBSP technology. There is no doubt that the advent of an SBSP system could be jumpstarted even sooner with accelerated efforts. The messaging of this thesis is to emphasize U.S. sponsorship of SBSP technology development with attention on DOD-specific opportunities.

1. Space Segment

The bulk of required advancements are in the space segment of the SBSP system, which is encompassed by the SPS. Many aspects of a SPS would be trailblazing due to the technology involved in its design, assembly, and implementation. These reasons warrant expanded efforts for the DOD to invest and support the maturation of power beaming technology.

Jaffe et al.'s report in 2019 specifically recommends the leadership to fall under the Under Secretary of Research and Engineering, through the Operational Energy Capability Improvement Fund (OECIF), with engagement from the ONR, the Directed Energy Directorate of AFRL, DARPA's Tactical Technologies Office, NASA, and similar entities. There is significant attention from these organizations and most of the existing research was born from these organizations. The major proving ground in power beaming lies in its distance, efficiency, and power level. If DOD becomes a major player in this technological area, they will surpass parity with foreign developments and be the first to realize an operational SBSP system.

An additional recommendation of this thesis for the space segment is to manage and follow advancements of the space robotics and iSA technologies. There is no existing or foreseeable launch vehicle with the required thrust or fairing size to accommodate the size and mass of a SPS, so a modular SPS design is most likely to be designed. It is certain that complex operations for the hardware and software of space robotics and iSA would be required to unify these modular pieces, with lots of work left to be done. There is ongoing development in this area, with the James Webb Space Telescope's recent successful launch that demonstrated remote self-deployment to solve the limit of fairing size. This capability is still in need of major breakthroughs that already has attention from NASA and the astronomical community in its significance.

2. Ground Segment

The ground segment needs to be well understood to accommodate missions at the tactical edge. It is recommended that, whatever the surface area that is required, resources be put towards research in compact or foldable rectenna arrays for ease of packing, transport, and storage. It is difficult for the DOD to adopt a new energy solution if it is more burdensome and time-consuming to get to the warfighter.

Additionally, it is recommended to focus on researching the deployment and serviceability of the receiving station. SBSP cannot be a viable solution if its effectiveness relies on the need of a solar power engineer's presence. A tactical receiving station is a paradigm shift that would completely transform the manner in which DOD conducts missions for expeditionary forces. This could improve the warfighter's capability by allowing more power-hungry devices to be employed.

3. Spectrum Requirements

It is not enough to develop a functional SBSP system. The regulatory hurdle of frequency allocation is a process that is required for all space assets performing signal transmissions. It is highly recommended to begin this paperwork and commence the processes to earmark candidate frequencies. This gives power beaming the benefit of formal documentation and recognition by the NTIA as a potential capability, giving it more weight to provision frequencies when the necessary studies are carried through. The obvious benefits are the prevention of major interference and chaos, otherwise rendering the system useless. The DOD must act on this first so the foundation of SBSP operation is cleared and gains acceptance amongst the international regulatory bodies.

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