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Exploring the feasibility of providing electrical power to remote bases via space-based solar power satellites

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THESIS

EXPLORING THE FEASIBILITY OF PROVIDING ELECTRICAL POWER TO REMOTE BASES VIA SPACE-BASED SOLAR POWER SATELLITES

by

David J. Chow

June 2013

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EXPLORING THE FEASIBILITY OF PROVIDING ELECTRICAL POWER TO REMOTE MILITARY BASES VIA SPACE-BASED POWER SATELLITES

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

Delivering electrical power to remote military bases can be an expensive and dangerous task. The idea of delivering renewable power to remote military bases through space-based solar power has existed for many years, but has not yet materialized. This research sought to examine existing studies and leverage their findings to determine a systems architecture and subsequent design alternatives that could deliver space-based solar power to a military base in Afghanistan. Three design alternatives were created and were based on the defined systems architecture. The system attributes vary by design alternative, to include transmitter size, rectenna size, power transmitted, mass of components, and number of launches required. The design attributes were weighted accordingly to stakeholder objectives. In turn, the entire design alternative was given a Measure of Effectiveness score. This score was used to determine the most effective design alternative among the designs presented in this research. The result is one of the three designs conclusively meets stakeholder requirements and is more effective than the others, yet further research should be done to improve the design and address other concerns, such as the extremely high cost of the system and the potential environmental and safety issues of the high-power microwave beam.

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LIST OF ACRONYMS AND ABBREVIATIONS

AF	Air Force
ASA ALT	Assistant Secretary of the Army for Acquisition, Logistics, and Technology
ASN RDA	Assistant Secretary of the Navy for Research, Development, and Acquisition
CONOPS	Concept of Operations
CONUS	Continental Unites States
DC	Direct Current
DoD	Department of Defense
DoE	Department of Energy
ERDA	Energy Research and Development Agency
ESA	European Space Agency
FEMP	Federal Energy Management Program
FOB	Forward Operating Base
GEO	Geostationary Orbit
GHz	Gigahertz
GTO	Geosynchronous Transfer Orbit
GW	Gigawatt
IED	Improvised Explosive Device
JAXA	Japanese Aerospace Exploration Agency
kg	Kilogram
KPP	Key Performance Parameter
LSP	Lunar Solar Power
m^2	meter-squared
MOE	Measure of Effectiveness
MOP	Measure of Performance
MW	Megawatt
N/A	Not Applicable
NAS	National Academy of Sciences

NASA	National Aeronautics and Space Administration
NSF	National Science Foundation
NRC	National Research Council
OCONUS	Outside Continental United States
OTA	Office of Technology Assessment
POG	Power on Ground
R&D	Research and Development
RF	Radio Frequency
ROM	Rough Order of Magnitude
SAF/AQ	Assistant Secretary of the Air Force for Acquisitions
SECDEF	Secretary of Defense
SSP	Space-based Solar Power
TBD	To Be Determined
TRL	Technical Readiness Level
TW	Terawatt
USA	United States Army
USD	United States Dollar
USAF	United States Air Force
USN	United States Navy
W	Watt
WBS	Work Breakdown Structure
W/kg	Watt per kilogram
W/m^2	Watts per meter squared
WPT	Wireless Power Transmitter

EXECUTIVE SUMMARY

Delivering electrical power to remote military bases can be an expensive and dangerous task. The idea of delivering power to these remote military bases through space-based solar power satellites has existed for many years, but it has not yet materialized. Early concepts were too expensive and the needed technology was not mature. In more recent years, technology has improved and there has been an increasing focus on renewable energies and energy efficiencies. The focus of energy has received attention from world leaders as well as from the United States of America, to include the countries' president and its military forces.

One concept for delivering large amounts of renewable energy is through a space-based solar power satellite system. This research sought to leverage existing studies to determine a systems architecture and subsequent design alternatives that could deliver space-based solar power to a military base in Afghanistan. To determine the systems architecture, this research analyzed the architectures from John C. Mankins and utilized the system engineering process from D.M Buede, which included gathering stakeholder requirements, establishing an objectives hierarchy, and conducting a functional analysis. The systems architecture and the research of Raul G. Gómez et al. were then used to create three design alternatives which meet the power requirements of the stakeholders.

The final part of this research sought to determine which design was most effective according to stakeholder requirements. The system attributes varied by design alternative, to include transmitter size, rectenna size, power transmitted, mass of components, and number of satellite launches required. The final design attributes were weighted accordingly to stakeholder objectives. In turn the entire design alternative was given a Measure of Effectiveness score. This score was used to determine the most effective design alternative among the designs presented in this research. The result is that one of the three designs conclusively meets the stakeholder requirements and is more effective than the others, yet further research should be done to improve the design and address other major concerns, such as the extremely high cost of the system and the potential environmental and safety issues of the high power microwave beam.

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I. INTRODUCTION

A. OBJECTIVE

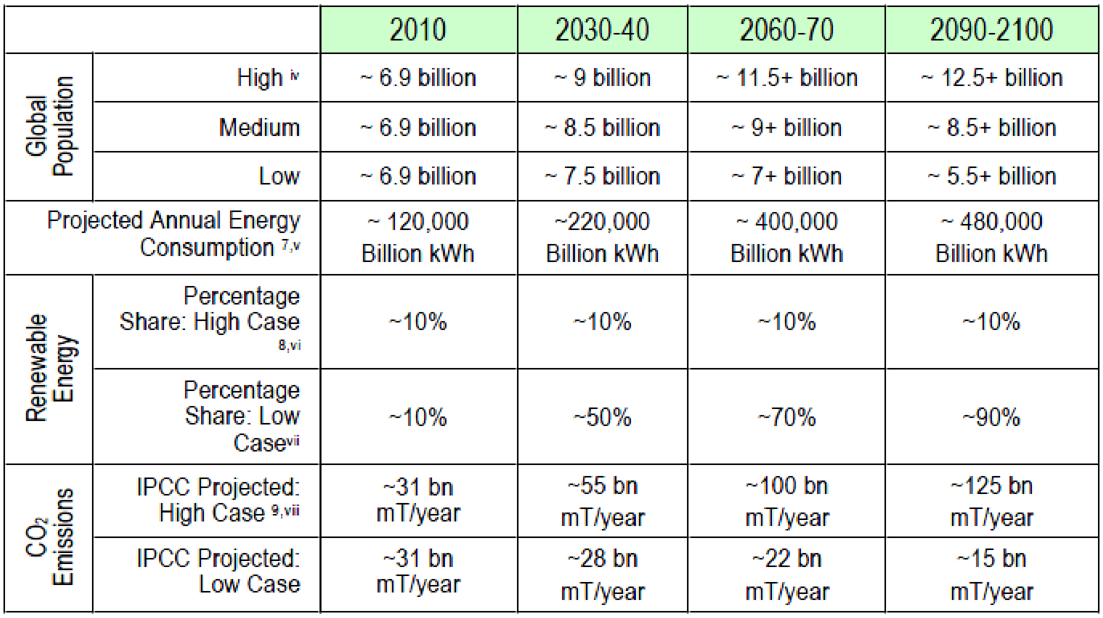
The research and conclusions within this paper are targeted at finding the best system design alternative for using Space-based Solar Power (SSP) satellites for military bases in Afghanistan, where energy is expensive and/or very difficult to obtain.

B. BACKGROUND

1. The Global Energy Situation

The global energy situation is worsening. In the coming years, more efficient energy sources will need to be developed and implemented. This is driven primarily by three factors. First, there is a growing demand for energy to feed the economic demand. Second, there exists growing concerns regarding long-term accumulation of fossil fuel-driven green-house gases in the earth's atmosphere. Third, the prospect exists that global production of petroleum and other fossil fuels will peak and possibly decline in the next few decades. John Mankins is a researcher in SSP and has done extensive studies on the current and future state of the world's energy. He forecasts the annual energy consumption for the next 100 years and shows an exponential relationship between energy needs and the increase in population. He also takes the position that a baseline would require two-times the level of energy consumption in 2010 by 2030–2040, and four-times the 2010 amount by 2090–2100 (Mankins 2011, 1–2). Table 1 provides a summary of forecasts for global population, renewable energy, and CO_2 emissions for the years starting in 2010 to 2100. Mankins' key expertise is in advanced space systems concepts, space solar power, and technology research and development (R&D) management. He has contributed many studies in the space solar power discussion.

Table 1. Forecasts of future energy/environment factors (from Mankins 2011, 3)



		2010	2030-40	2060-70	2090-2100
Global Population	High [iv]	~ 6.9 billion	~ 9 billion	~ 11.5+ billion	~ 12.5+ billion
	Medium	~ 6.9 billion	~ 8.5 billion	~ 9+ billion	~ 8.5+ billion
	Low	~ 6.9 billion	~ 7.5 billion	~ 7+ billion	~ 5.5+ billion
Projected Annual Energy Consumption [7,v]		~ 120,000 Billion kWh	~220,000 Billion kWh	~ 400,000 Billion kWh	~ 480,000 Billion kWh
Renewable Energy	Percentage Share: High Case [8,vi]	~10%	~10%	~10%	~10%
	Percentage Share: Low Case[vii]	~10%	~50%	~70%	~90%
CO_2 Emissions	IPCC Projected: High Case [9,vii]	~31 bn mT/year	~55 bn mT/year	~100 bn mT/year	~125 bn mT/year
	IPCC Projected: Low Case	~31 bn mT/year	~28 bn mT/year	~22 bn mT/year	~15 bn mT/year

2. United States' Call for Usage of Efficient Energy Sources

The United States of America has taken several steps to help utilize more energy efficient practices. In Executive Order 13423, the U.S. president provides clear policy for federal agencies to "conduct their environmental, transportation, and energy-related activities under the law in support of their respective missions in an environmentally, economically and fiscally sound, integrated, continuously improving, efficient, and sustainable manner" (U.S. President 2007, sec. 1–11). He further explains the goals for each federal agency head. One of these goals relates to the reduction of greenhouse gas emissions and seeks to

> improve energy efficiency and reduce greenhouse gas emissions of the agency, through reduction of energy intensity by (i) 3 percent annually through the end of fiscal year 2015, or (ii) 30 percent by the end of fiscal year 2015, relative to the baseline of the agency's energy use in fiscal year 2003 (U.S. President 2007, sec. 1–11).

The second goal relates to renewable energy and states that,

> (i) at least half of the statutorily required renewable energy consumed by the agency in a fiscal year comes from new renewable sources, and (ii) to the extent feasible, the agency implements renewable energy generation projects on agency property for agency use. (U.S. President 2007, sec. 1–11).

Federal agencies can meet these goals with the increased usage of renewable energy. Federal agencies must submit fiscal year reports to the Department of Energy (DoE) according to the Federal Energy Management Program (FEMP) (U.S. DoD Annual Energy Management Plan 2010, 1). These yearly reports summarize the submitting agencies' energy management programs and measure their progress against the energy performance goals.

3. DoD's Initiative to Manage Energy Usage

The Department of Defense (DoD) utilizes one percent of the total U.S. consumption of energy. Although this may seem to be an insignificant overall amount, the DoD is the largest single consumer of energy in the U.S. By comparison, the country of Nigeria, with over 140 million people, consumes less energy than the DoD (Karbuz 2007) while in 2012, the DoD in comparison employs about 3.2 million people (Alexander 2012). The DoD per capita energy consumption is approximately 10 times more than a single person in China (Karbuz 2007). Statistics such as these help explain why top U.S officials are calling to utilize renewable energy sources instead of traditional sources, especially within the DoD.

The DoD has taken several steps to meet the requirements set before them by the President and the DoE. In order to meet the annual fiscal report requirement, the DoD submits the Annual Energy Management Report. The report highlights the topics of facilities energy use, energy intensity level, renewable energy use, water intensity levels, and continuing initiatives to maintain energy program improvements. The report includes individual statistics for the U.S. Army (USA), U.S. Navy (USN), U.S. Air Force (USAF), and statuses the goals set by Executive Order 13423.

At the department level, the USAF, for example, releases several reports to support the DoD Annual Energy Management Plan. Some of these reports include the Air

Force (AF) Energy Plan, AF Infrastructure Plan, and AF Aviation Operations Energy Plans. These reports focus on specific areas within the department in order to properly manage and set goals for energy.

4. Powering Military Bases in Remote Areas

The White House also expresses its concern for military bases and their use of energy. A released statement emphasizes the inherent connection between energy independence and national security. As a response to President Obama's 2012 State of the Union, the White House statement explains that the DoD has the goal of meeting 25 percent of its energy needs with renewable energy by 2025, with the Army, AF, and Navy making commitments of deploying 1 gigawatt (GW) of renewable energy each by the deadline. Renewable energy is important to making our bases more energy secure, and through renewable energy implementation the DoD is better able to carry out its mission to defend the nation by being less dependent upon fossil fuels (U.S. Press Secretary 2012).

The implementation of more energy efficient sources is especially important for oversea and remote military bases. Not only does the use of more efficient and renewable sources reduce emissions that harm the environment, but it also reduces the risk to the warfighter on the battle field. The use of fossil fuels on the battlefield may run low for one reason or another and may put lives at risk, but the use of sustainable resources of power can reduce this risk (Indian Energy 2012). The use of renewable energy for remote military bases, including Forward Operating Bases (FOB), is crucial as they are "currently heavily dependent on long-distance deliveries of significant quantities of bulk fuel" (U.S. Office of Naval Research 2010). For covert bases, every flight or vehicle leaving and arriving at the facility on a fuel-providing mission compromises secrecy and the mission. In a timely mission, being able to operate at full energy capability may be the difference between a successful or failed mission, or even the difference of life and death. The ability to reduce the usage of fossil fuels and the ability to increase dependency upon renewable energy sources is a key aspect to supporting the mission for oversea bases.

5. Renewable Energy Through Space-Based Solar Power (SSP) Solutions

Solar power is one form of renewable energy that can reduce the use of fossil fuels. The use of solar panels on earth, however, is far less reliable than utilizing fossil fuels because the technology is dependent upon favorable weather conditions and much of the sun's solar power is lost through the earth's atmosphere. The concept of a SSP solution addresses these issues. First, solar panels placed in space are not deterred by earth's atmospheric weather. Secondly, the solar power available in space is greater than on earth. The solar flux available in geostationary orbit (GEO) is constantly 1360 W/m^2 as compared to the surface of Earth's 600 W/m^2 in optimal season, weather, and time of day (Gómez et al. 2009, 22). This means that at most the earth will receive half of the amount of solar energy as compared to GEO. On average, photovoltaic arrays in GEO receive eight times the amount of sunlight as opposed to on earth (Price 2001).

a. Space-Based Solar Power Satellite

Dr. Peter Glaser first coined the concept of SSP satellites in the late 1960s, just years after Russia's 1957 Sputnik, the inaugural worldwide space launch event. Glaser's idea consists of a large platform positioned in a high earth orbit that continuously collects solar power and converts it into electricity. The electricity generated helps drive a wireless power transmitter (WPT) system that transmits the electricity to earth. This concept is captured in Figure 1 and is taken from Dr. Glaser's 1973 patent (Mankins 2011, 6).

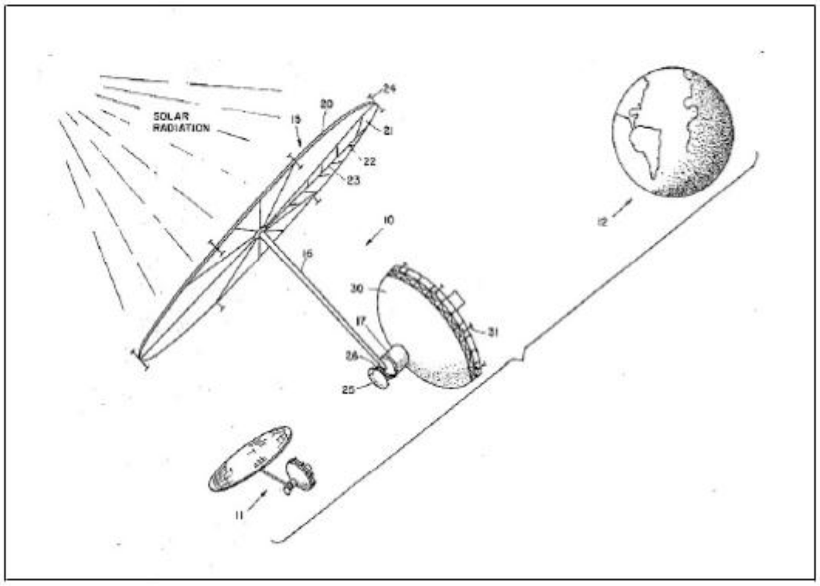


Figure 1. Illustration of Glaser’s SPS Concept from the 1971 Patent (from U.S. Patent Office and Trademark Office, patent no. 3781647)

At the time of his patent, the worldwide space community did not believe Dr. Glaser’s concept was realizable in the next few decades. Because of this, shortly after initial publication of the concept, research progressed slowly. The U.S. conducted further research through Energy Research and Development Agency (ERDA) – the DoE predecessor – and National Aeronautics and Space Administration (NASA). Due to unfavorable reviews of the near-term feasibility by U.S. Congress Office of Technology Assessment (OTA) and National Research Council (NRC), government sponsored activities were cancelled. It was not until after the year 2000 that independent research by U.S. National Academy of Sciences (NAS) and NRC showed that SSP was a solution feasible in the next couple decades. The R&D path to developing these satellites showed to be of great potential to future space endeavors. As a result, studies have increased on a global scale by such agencies as National Science Foundation (NSF), Japanese Aerospace Exploration Agency (JAXA), European Space Agency (ESA) and the DoD (Mankins 2011, 8).

b. Space-Based Lunar Solar Power

The idea of space-based lunar solar power (LSP) was originally developed by David R. Criswell in 1985. His concept approaches the renewable energy issue by placing a large solar power harnessing system on the surface of the moon. The system would take the harnessed power and beam it to earth for use. Criswell's studies show that in the year 2050, commercial sources will need to provide at least 2 kilowatts of electricity per person, or 20 terawatts (TW) globally. According to his research, the moon receives 13,000 TW of solar power incidence and that facilities built on the moon can potentially deliver more than the needed 20 TW of affordable electric power to Earth. Criswell's concept consists of four main elements: the sun, the moon, the power beam from the moon to the earth, and the rectenna which receives the beam (Criswell 2004, 682–686). A rectenna is a rectifying antenna, which is a special type of antenna used to convert received microwave energy to usable direct current electricity. William Brown describes the term "rectenna" being used generically for the receiving aperture of any beamed power transmission system that combines the function of capture and rectification. At the core, a rectenna's functions are power collecting, harmonic filtering, and rectification into DC power (Brown 1992, 1244). This concept of space-based lunar solar power is depicted in Figure 2.

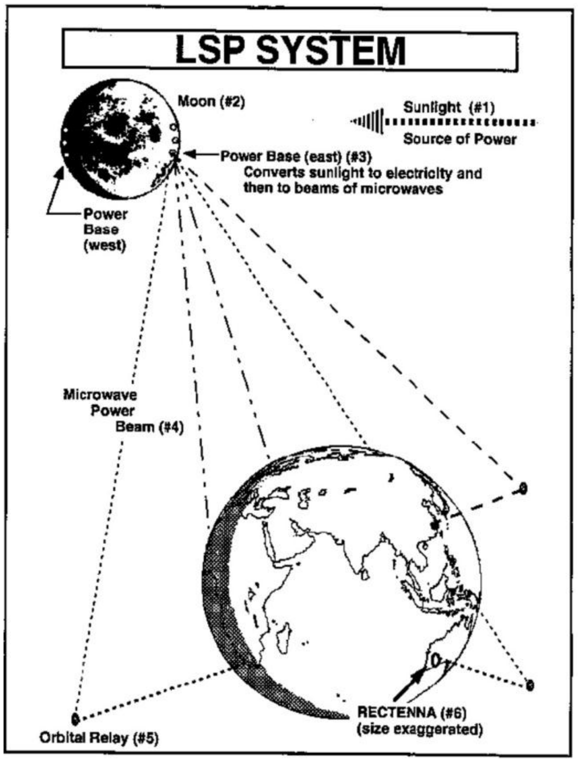


Figure 2. Space-based lunar solar power operational overview (from Criswell 1996, 5)

Space-based LSP has several advantages compared to SSP satellites. The first advantage is that the moon is a stable and predictable platform. Secondly, the moon contains all the needed materials for solar cells and structures, greatly reducing the potential amount of equipment required to transport from earth to space. Thirdly, because of the large physical size of a satellite system, its presence requires a large amount of real estate in its selected orbit. A lunar solution is far less intrusive to other satellites and greatly reduces the risk of being in the path of another satellite constellation or space debris. Lastly, access to the moon is potentially greater and safer, increasing overall maintainability and worker safety (Kulcinski 2001, 3).

C. SCOPE, BOUNDS, AND ASSUMPTIONS

This thesis focuses on finding a system architecture and a design alternative that will fulfill the needed power for a remote military base in Afghanistan. The physical design must be deployable in Afghanistan using existing transportation. The system must be able to provide reliable and consistent power to the corresponding base for nearly 24-hours a day, 365-days a year. Additionally, the system must provide 100% of the base’s operational power needs during this time period. Figure 3 provides current solution overviews that meet this requirement for powering a remote military base.

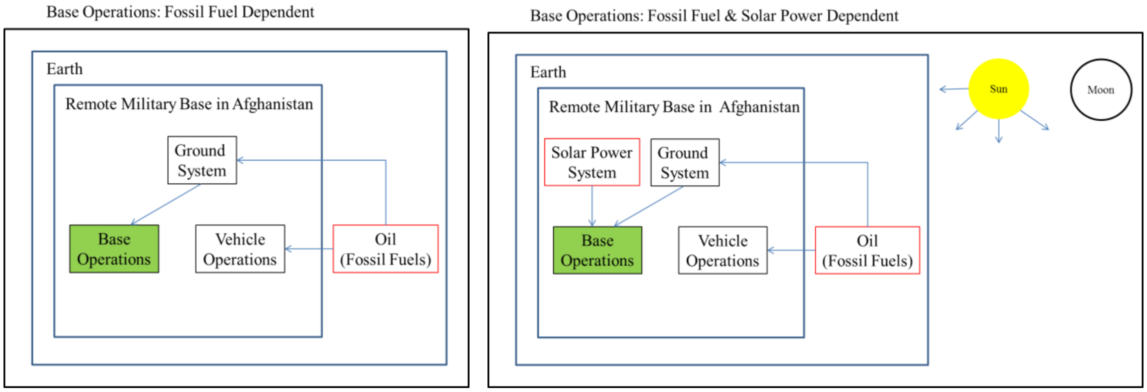


Figure 3. Current solutions for powering base operations

Space-based solar power satellites, as depicted by Dr. Glaser, are the assumed concept for this thesis in order to fulfill the need to use renewable energy. The SSP architecture and design alternative is open for discussion in this thesis. Another assumption, based on research and findings, is that the technology needed for SSP already exists and the system is technically feasible. Figure 4 illustrates the assumption of using SSP and also defines the scope of this thesis within the overall system of powering a remote military base in Afghanistan by the dotted green line.

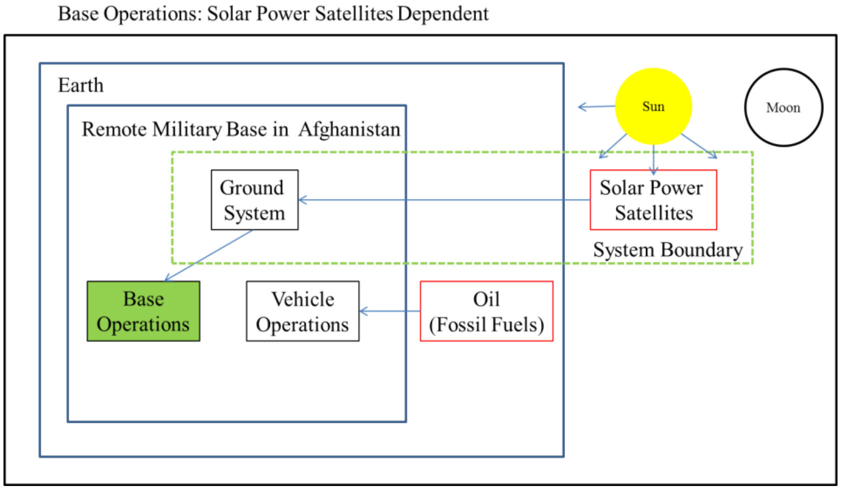


Figure 4. Scope and bounds of this thesis

The estimates and analysis conducted in this study applies to powering electrical equipment that supports a military base's operational power needs only. The energy required to power items like aircraft, cars, tanks, etc., are outside the scope of this research. Operational power needs include items such as communication devices, runway and street lighting, and generators, to name a few. Items such as computers, cooking equipment, housing infrastructure, and other energy-consuming devices are also included. When a Rough Order of Magnitude (ROM) estimate is provided for total energy use at a military base, the assumption is that the ROM estimate includes operational power needs only.

D. SYSTEMS ENGINEERING METHODOLOGY AND APPROACH

The study primarily follows the systems engineering approach as defined by D.M. Buede in his 2009 work The Engineering Design of Systems. A graphical representation of this approach is presented in Figure 5. For the scope of this study, steps from nodes A111 through A114 are used. The following describes what takes place during each step of the systems engineering approach.

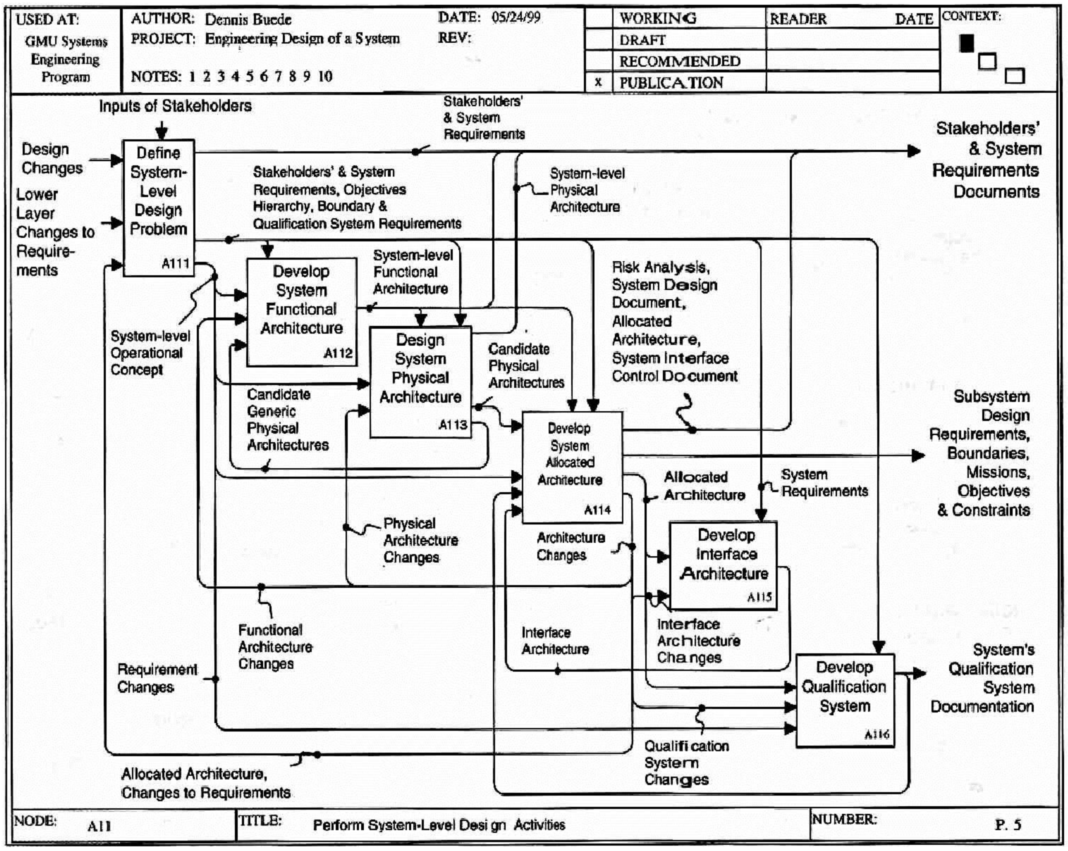


Figure 5. D.M. Buede systems engineering approach (from Buede 2009, 460)

1. The first step in the systems engineering approach, as represented in Figure 5 by node A111, is to define the system-level design problem. This step begins by understanding who the stakeholders are, what the user requirements are, what deficiencies are in the current system, and the potential interfaces of a future system. Understanding these areas will help to define a concept of operations (CONOPS), a system objective hierarchy, and system boundaries.
2. The second step in the systems engineering approach, as represented in Figure 5 by node A112, will be to design a system functional architecture. This section begins by establishing the simple functionalities for the operational concept. The result of establishing functionalities and an operational concept will lead to a draft, evaluation, and selection of a functional model.
3. The third step in the systems engineering approach, as represented in Figure 5 by node A113, is to develop a systems physical architecture. Taking into account the system functional architecture, this section will include a brainstorming of a generic physical architecture, will propose alternate physical architectures, and will recommend one of the physical architectures as best suited to meet the requirements.
4. The fourth step in the systems engineering approach, as represented in Figure 5 by node A114, is to develop the system allocated architecture. By taking into account the system functional architecture and system physical architecture, this section will briefly allocate functions and system-wide requirements to physical subsystems.
5. The fifth step, not included in Buede’s system engineering approach, is to create design alternatives based on the selected architecture presented in this thesis. An analysis of each design alternative will be conducted against the defined Measures of Performance (MOP) to determine the highest Measure of Effectiveness (MOE) score. The highest overall architecture MOE score will be the final recommended solution. The analysis of design alternatives will consider system objectives, requirements, functional, and physical aspects.

E. THESIS ORGANIZATION

Chapter I. This chapter presents background on the need for renewable energy within the U.S. Starting from the U.S. President, energy policy has been implemented down to the various military services. The overall theme is to become less dependent on fossil fuel forms of energy and to deploy further uses of renewable energy sources. Renewable energy sources are especially critical for use in remote military bases and FOBs. Variations of SSP are promising options for fulfilling the renewable energy requirement. Solutions presented are on orbit and on lunar solar powered systems. The chapter also presents an overview of the systems engineering process that is used in this thesis and presents the scope, bounds, and assumptions.

Chapter II. The focus of this chapter is to define the problem by first understanding who the stakeholders are. Gathering the requirements from stakeholders and filtering them through this thesis' scope, bounds, and assumptions will help develop a comprehensive needs list and an effective needs statement.

Chapter III. Through a comprehensive understanding of the requirements, functional characteristic to physical component flow diagrams will be generated. From these diagrams, an architecture and design alternatives can be created, and an analysis of these designs can be conducted to see how well the requirements have been met. Based on set MOPs, these designs can be scored and the best design alternative can be set forward. This chapter will also conduct a brief cost analysis.

Chapter IV. This final chapter will summarize the findings, make final conclusions, and will recommend areas for further study.

II. SYSTEM LEVEL DESIGN PROBLEM DEFINITION

A. PROBLEM STATEMENT

The DoD has the goal of meeting 25 percent of its energy needs with renewable energy by 2025, with the Army, AF, and Navy making commitments of deploying 1 GW of renewable each by the deadline. Renewable energy is important to making our bases more energy secure, and through renewable energy implementation the DoD is better able to carry out its mission to defend the nation by being less dependent upon fossil fuels (U.S. Press Secretary 2012).

The implementation of renewable energy sources is especially important for oversea and remote military bases. Currently, in order to obtain the necessary power levels, large amounts of oil are transported to the base, often through neighboring countries. Obtaining oil this way is very costly in unit price and requires teams for logistics and operations. This is the case for U.S. remote military bases in Afghanistan. In 2009, Pentagon officials stated that the fully burdened cost to deliver one gallon of gasoline to remote areas of Afghanistan was approximately $400 with outlier costs as high as $1,000. Additionally, dependency upon the delivery of oil introduces greater risk to human life. In 2008, 44 trucks and 220,000 gallons of fuel were lost due to attacks and other events when fuel was delivered to Bagram Air Field in Afghanistan. Some 80 percent of U.S. military casualties in Afghanistan are a result of improvised explosive devices (IED), which are primarily placed on supply convoy paths (Tiron 2012). With 18,207 kilometers out of 21,000 kilometers of unpaved road in Afghanistan, threat of IEDs is a very real problem (Blanchfield 2005).

These facts regarding oil and the situation in Afghanistan address the need for more efficient power sources and renewable energy sources for remote military bases. Current suggestions and models have primarily focused around solar power solutions. Although this is a feasible resolution for stationary bases, the large amount of space and infrastructure required to deploy such a system renders this solution less than ideal for remote military bases, especially for those which may need to relocate often. An efficient and effective solution has yet to be deployed which meets the energy needs for an entire remote military base. The challenge therefore is to find a fast deployable solution efficient enough to power an entire remote military base while eliminating the need and dependency for fossil fuels. The implications of acquiring this technology are potentially huge, even to the degree of saving human lives.

B. NEEDS ANALYSIS

1. Stakeholder Analysis

Establishing good requirements is often considered as the foundation and key of a systems engineering effort. The engineers must first focus their efforts and involvement in gathering requirements from the stakeholders. A stakeholder's requirement is an operational statement concerning their need. This is gathered by taking the stakeholder requirements and translating them into engineering terminology. Once requirements are established, it is the role of the systems engineers to provide a system that accomplishes the primary objectives set by the stakeholders, including those objectives associated with the creation, production, and disposal of the system (Buede 2009, 3, 52, 195).

A stakeholder analysis was conducted to gain a better understanding of the generally needed capability and determine big picture customer desires.

a. Stakeholders

(i) Policy and Decision Makers

- The President of the United States of America ultimately oversees policy and direction to strengthen the environmental and energy management of U.S. Federal agencies. In one of his executive orders, the President directs that U.S. federal agencies are to conduct their missions in an environmentally, economically and fiscally sound, integrated, continuously improving, efficient, and sustainable manner (U.S. President 2007, sec. 1–11).
- The DoD and the Secretary of Defense (SECDEF) are charged to provide the military forces needed to deter war and to protect the security of our country (U.S. Department of Defense 2013). The DoD, as a Federal agency, is therefore directly affected by Executive Order 13423 and must comply with the President's direction on environmental and energy management.

(ii) User Representatives

- Military bases of all services, located around the globe, assist the DoD to fulfill its mission. These bases and their personnel provide support of various kinds, some of which are acquisitions, maintenance, strategy development, operations, and policy. This includes continental United States (CONUS) and Outside the Contiguous United States (OCONUS) bases. Commanders of these bases are charged to fulfill their specific missions with the resources available.
- Combatant Commands have the responsibility of Operational Control, which deals with logistics of pushing supplies and fuel forward to deployed forces. They also field and maintain any system which is pushed forward. An example of a unit under a combatant command is the Marine Air-Ground Task Force Support Battalion 11.2 whose mission it is to "provide an armed escort for the local nationals" who carry the fuel to FOBs (Jackson 2012).
- Administrative Control Commands deal with organizing, training, and equipping combatant forces. Each service has their own administrative command which specifically assists deployed forces.
- The warfighter carries out the mission on all parts of the globe and sacrifices his own life. He may spend his time and energy planning and carrying out the gathering of resources and protecting of convoys containing critical resources. These forces support the warfighter on the front lines.

(iii) Acquisition Agents and System Developers

- The Assistant Secretary of the Air Force for Acquisitions (SAF/AQ), the Assistant Secretary of the Navy for Research, Development, and Acquisition (ASN RDA), and the Secretary of the Assistant Secretary of the Army for Acquisition, Logistics, and Technology (ASA ALT) are charged with the development and acquisition of military assets, such as weapon systems, buildings, and munitions.

b. Stakeholder Approach

The approach for capturing stakeholder needs was conducted based on research of officially released documentation at the Executive, DoD, and AF levels. These documents expressed general direction and instruction for agencies, but also include specific requirements. These documents created the framework for the user needs. In addition, ROM estimates were sought and found in various source documentations. These ROM estimates also helped to identify more specific needs of the stakeholders.

c. Rough Order of Magnitude (ROM) Power Estimates

Research provided ROM estimates of power needed to fully operate military bases. This information provides an initial baseline requirement for the needed amount of power that is desired. Research provided ROM estimates for powering two military bases:

- 45 MW estimate needed for Nellis AFB based on given data that 15 MW is 1/3 of total power (Karbuz 2007, 4).
- 135 MW estimate needed for National Guard Based Toledo, Ohio based on fact that 28.9 MW of electricity is 21.3% of total electricity consumed (U.S. DoD Annual Energy Management Plan 2010, 20).

2. Effective Needs Statement and Objectives Hierarchy

The United States military requires a system which can deliver power necessary to operate a remote military base, and must be delivered using an SSP architecture. Means of producing power other than SSP are available, but this study specifically seeks the best SSP design alternative for remote military base use and is therefore chosen for this study. The location of need is in the country of Afghanistan and all necessary power must support operations with minimal pause or deficiency. The system must be able to provide power between the amounts of 45 MW and 135 MW. The system must meet all requirements and be deployable in Afghanistan using currently available transportation. The Objectives Hierarchy in Figure 6 is derived based on the effective needs statement.

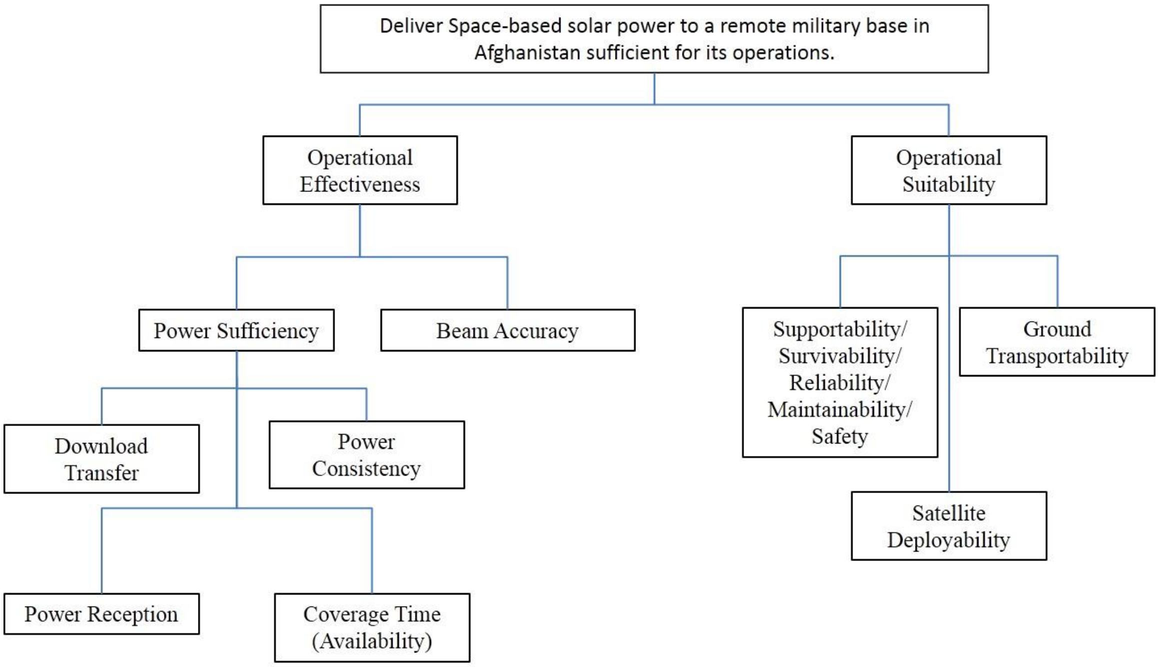


Figure 6. Objectives hierarchy

The Objectives Hierarchy of a system contains a hierarchical representation of the major performance, cost, and schedule characteristics that the stakeholders will use to determine their satisfaction with the system (Buede 2009, 57). For the scope of this thesis, performance is the primary focus. Schedule pertaining to system development is not considered in this thesis. Cost is not considered a primary objective in this research, but it is considered after the total design effectiveness is measured.

The Objectives Hierarchy begins with the overarching statement derived from the effective needs statement, which is to deliver SSP to a remote military base in Afghanistan sufficient for its operations. From this statement, the hierarchy is divided into two main objectives, Operational Effectiveness and Operational Suitability. Operational Effectiveness is divided further into Power Sufficiency and Beam Accuracy. Power Sufficiency consists of the satellite's Download Transfer, Satellite's Coverage Time (Availability), Power Consistency, and Power Reception. The use of the term "availability" is defined as "the probability that a system or equipment, when used under stated conditions in an *ideal* support environment, will operate satisfactorily at any point in time as required" (Blanchard and Fabrycky 2011, 426–427).

In addition to Operational Effectiveness, Operational Suitability is the second objective under the overarching effective needs statement. Operational Suitability consists of Ground Transportability and Satellite Deployability. Operational suitability also consists of system supportability, survivability, reliability, maintainability, and safety, but these are not specific areas investigated by this thesis.

III. DESIGN AND ANALYSIS

A. FUNCTIONAL ANALYSIS

The functional analysis section begins with the operational concept for the SSP system powering a remote military base in Afghanistan. Functional analysis is an integral part of decomposition in the “Vee” process model, the left side in Figure 7. The derived architectures help trace user requirements to the final end product design.

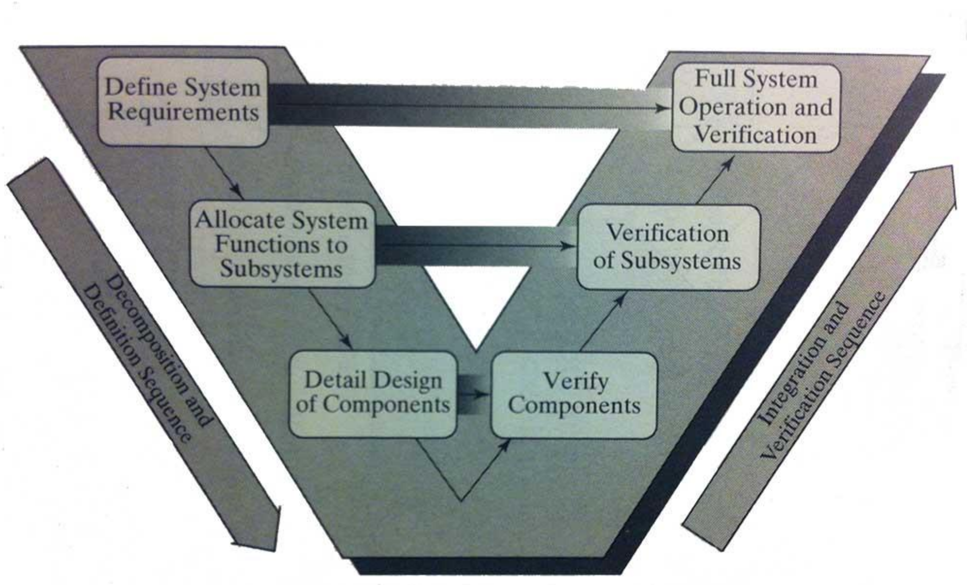


Figure 7. “Vee” process model (from Blanchard and Fabrycky 2011, 37)

The three architectures are essential to forming the proper context and understanding of the entire system. The functional architecture defines what the system must do. The physical architecture represents partitioned physical resources available in order to meet the system’s functions. The allocated architecture displays the mapping of functions to the available resources in a discrete-event simulation of the system’s functions (Buede 2009, 27).

1. Simple Functionalities for Operational Concept

A simple functionality is “an ordered sequence of functional processes that operate on a single input to produce a specific out” (Buede 2009, 215). These simple functionalities do not necessarily name all the required inputs for the mentioned output. Additionally, not all functional processes required to obtain the desired output may be named. Table 2 below is a flow of simple functionalities. The complete rows starting with "solar power" and "receive power beam" pertain to the boundaries and scope of this thesis.

Table 2. System simple functionalities

Input	**Simple Function**	**Output**
Positioning/pointing data	Translate incoming data	Data to transportation system
Solar power	Convert power	Power beam
Receive power beam	Convert power	Usable power

The operational concept in Figure 8 incorporates the simple functionalities from Table 2 and stakeholder requirements and is adapted from Donald Rapp (Rapp 2007, 18).

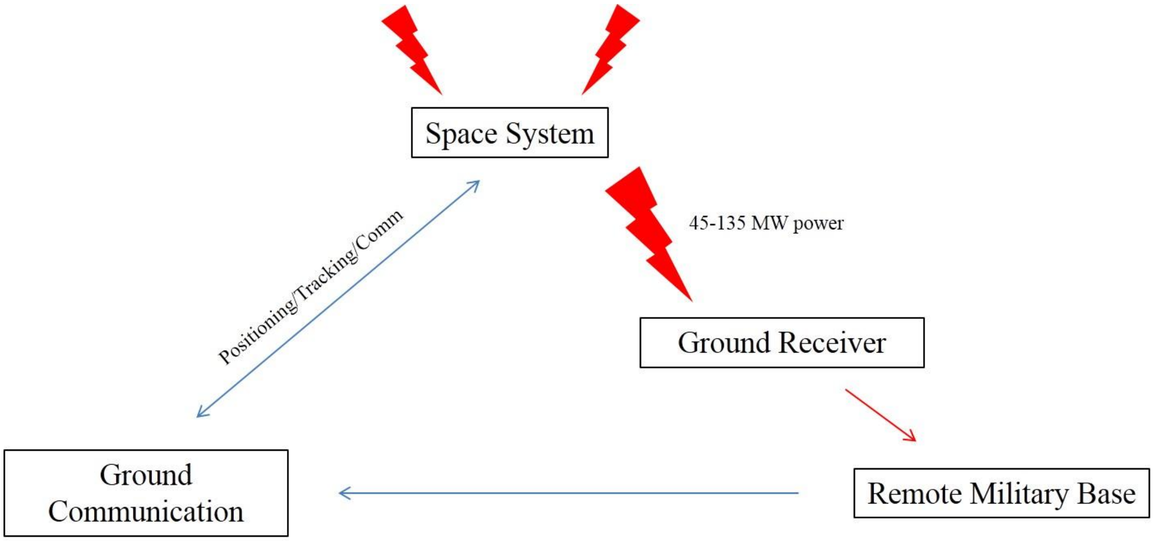


Figure 8. Operational concept overview

2. Functional Architecture

A functional architecture of a system contains a hierarchical model of the functions performed by the system, its components, and its configuration items (CI). The functional architecture can be defined at several levels of detail according to Buede. First, it can be defined as a logical architecture that defines what the system must do – a decomposition of the system's top-level function. Second, Buede defines functional architecture as a logical model that captures the transformation of inputs into outputs using control information. Lastly, he defines it as a logical model of a functional decomposition plus the flow of inputs and outputs, to which input/output requirements have been traced to specific functions and items (Buede 2009, 211–216).

The generic functional architecture shows an overview of how the system will capture energy from the sun and transport this captured energy for use at the remote military base in Afghanistan. The generic functional architecture presented in Figure 9 is based on Mankin's Generic SPS Functional Architecture provided in his international assessment of space solar power (Mankins 2011, 18). The functional architecture presented in this thesis sought to simplify Mankin's architecture to an even higher level in order to stay within the reasonable scope of this thesis.

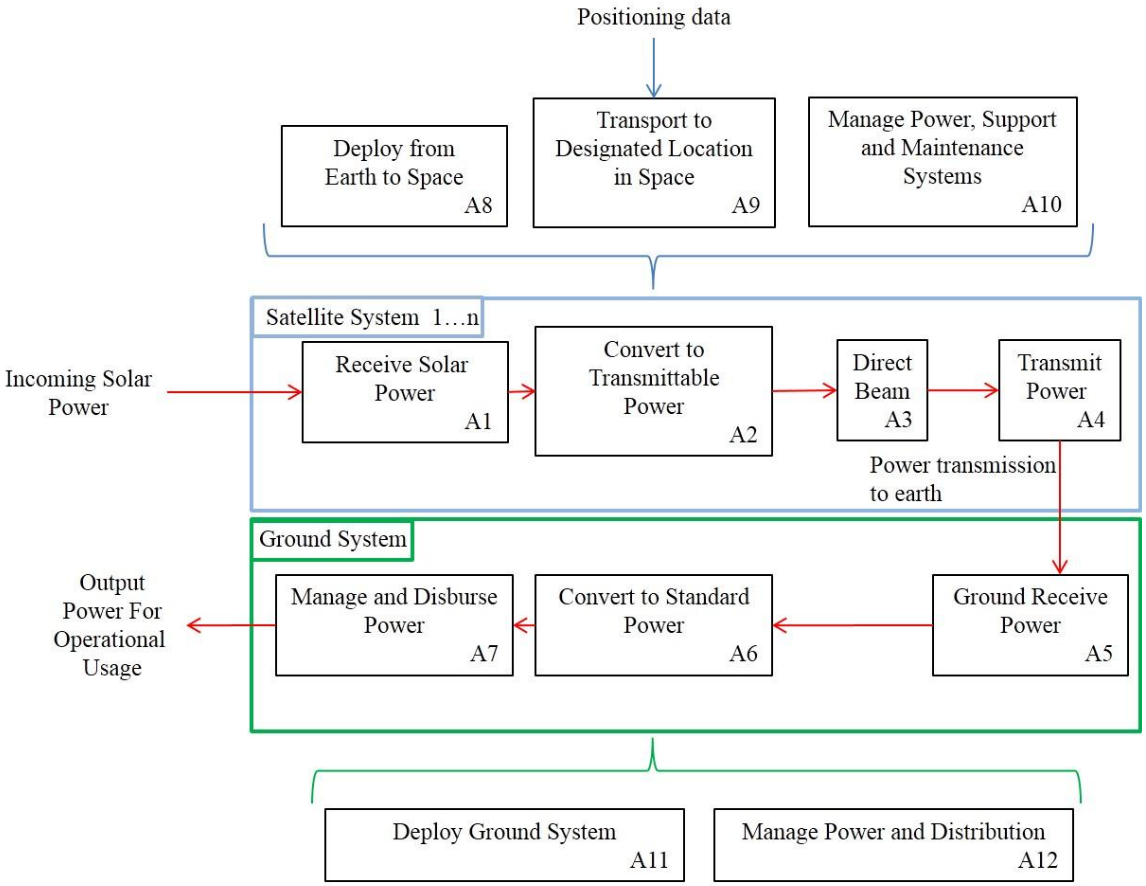


Figure 9. Generic functional architecture

The generic functional architecture in Figure 9 is used to answer the following questions:

- What primary functions are involved in order to provide a remote military base with SSP?
- What are the high-level inputs and outputs involved with a SSP system?

The functional architecture is composed of seven primary functions and five supporting functions. The system is decomposed into the following functions and is shown in Figure 9:

- Receive Solar Power (A1) includes receiving the sun's solar arrays into the appropriate form for use.
- Convert to Transmittable Power (A2) receives the collected power and converts the power into a specified form for later use in the system.

- Direct Beam (A3) rotates the transmitter to be aimed directly at the ground receiver on earth.
- Transmit Power (A4) accepts the power and transmits it to a designated location.
- Ground Receive Power (A5) receives the transmitted power from the space system transmitter.
- Convert to Standard Power (A6) includes accepting the received transmitted power and converting it into a usable form for final use.
- Manage and Disburse Power (A7) sends the converted power to the areas designated by the user. This may be a single output line or include multiple lines for disbursement.
- Deploy from Earth to Space (A8) includes taking the space system from earth into space.
- Transport to Designated Location in Space (A9) takes the in-space system and maneuvers it to the designated location in preparation for its primary mission.
- Manage Power, Support and Maintenance Systems (10) involves managing and monitoring of power on the space system, the receiving and sending of messages to ground operators, as well as receiving, processing and sending information to keep the system operational.
- Deploy Ground System (A11) includes taking the ground power receiver and transporting it and deploying it at the user's location.
- Manage Power and Distribution (A12) monitors the overall power being received from the satellite and distributed by the ground system to the operational user.

The flow of the generic functional architecture starts on the left side of the diagram with the incoming solar power to A1 where the system receives the solar power. The primary focus of interest is the flow of logic from A1 to A7 where the power is lastly disbursed for operational use to the user. The box around A1 to A4 is labeled "Satellite 1…n" because the architecture is open to having multiple solar power satellites if needed. The top brackets encompassing functions A8, A9, and A10 apply to the entire satellite segment of the system. The bottom brackets encompassing functions A11 and A12 apply to the entire ground segment of the system.

3. Physical Architecture

The physical architectures presented in this section are hierarchical descriptions of the physical resources available for this system. The architectures contain top-level components and progress down to the configuration items. The configuration items can be hardware, software, or can be a combination of hardware and software, people, facilities, procedures, and documents such as user manuals. To develop the architectures, a top-down process is used by developing one level of the tree at a time. By developing the architecture in parallel with the functional architectures, the design of both architectures can be evaluated to determine their effectiveness in meeting the requirement objectives.

There are several elements of physical architectures that have been decided specifically for this research. First, Buede makes a clear distinction between generic physical architectures and instantiated physical architectures. He explains that generic physical architectures provide resources for every function identified in the functional architecture. For all requirements addressed in the functional architectures, there must be a physical architecture associated without any specification of the performance characteristics of the physical resources. The instantiated physical architecture is a further extension of the generic physical architecture to which complete definitions of the performance characteristics of the resources are added (Buede 2009, 253–256). While this study does address several performance characteristics, instantiated physical architectures are specifically created. A second element of physical architectures that has been decided is that this study will not address the development of procedures for users of the system to follow, such as operating, maintenance, training, or support instructions usually included in operating manuals.

The physical architecture in Figure 10 is derived from tracing the functional architecture to physical sub-systems. This architecture can be used as a simple program Work Breakdown Structure (WBS) as defined in MIL-STD-881B [1993] for Defense Material Items. This figure represents the WBS as high-level key sub-systems and is decomposed further in the design process.

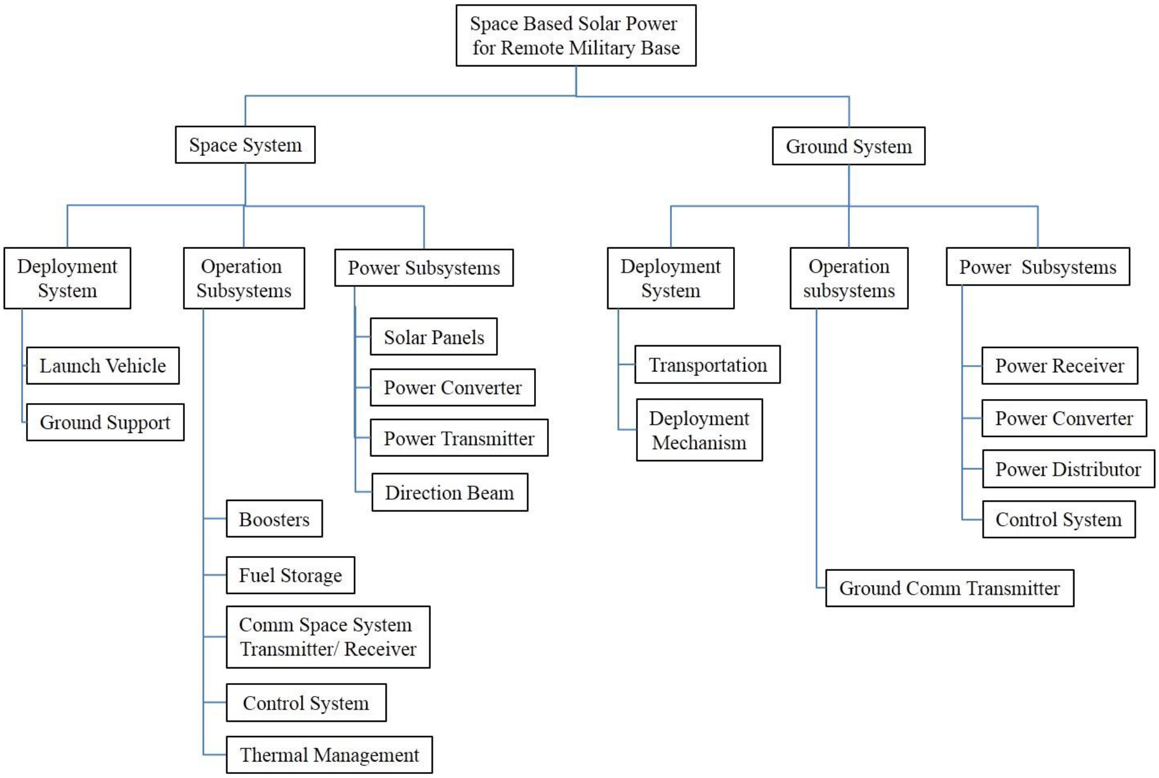


Figure 10. High-level physical architecture

4. Allocated Architecture

The allocated architecture integrates the requirements decomposition with the functional and physical architectures. Figure 11 considers the functions from the functional architecture and system requirements and allocates them to a physical subsystem. By doing this, the function of each subsystem is defined by the linked physical architecture component. All functions have a one-to-one traceability to the physical architecture component and vice versa, to which D.M Buede explains as being tremendously beneficial when allocating input and output items to internal and external interfaces (Buede 2009, 299).

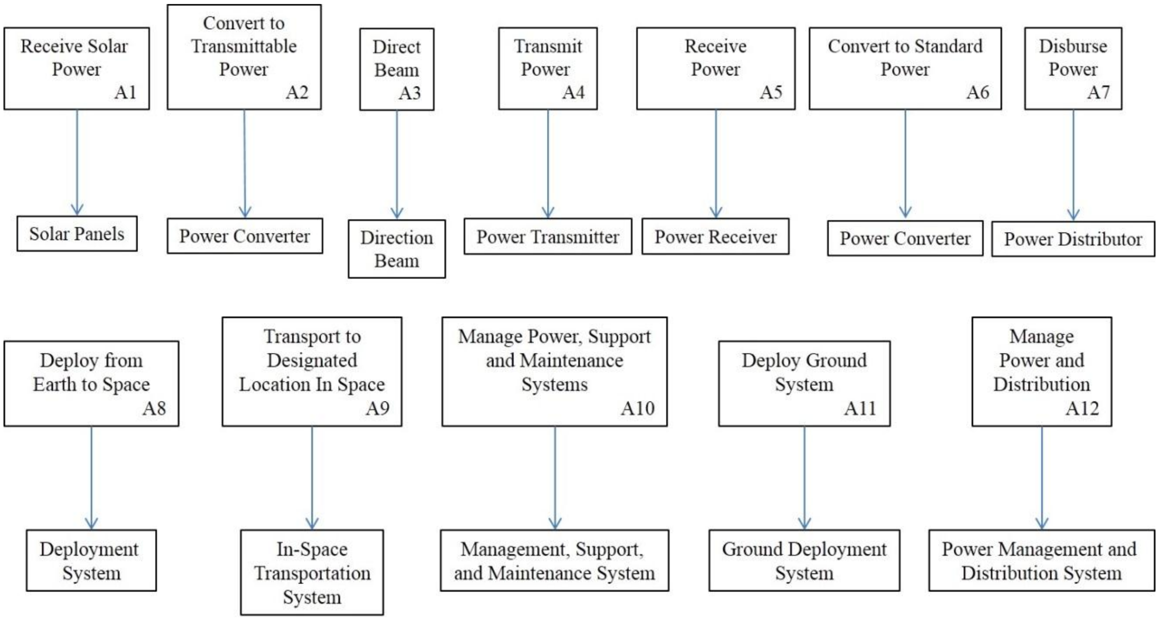


Figure 11. Allocated architecture

According to Buede, there are five major activities associated with the development of the allocated architecture. The first major activity is to allocate functions and system-wide requirements to physical sub systems. The second is to define and analyze functional activation and control structure. Thirdly, completing the allocated architecture includes conducting performance and risk analyses. The fourth major activity is to document architectures and obtain approval. The last major activity is to document subsystem specifications (Buede 2009, 285–286). For the scope of this thesis, the first three major activities are addressed minus the risk analysis.

B. VALUE SYSTEM DESIGN AND ANALYSIS

1. Weighted Objective Hierarchy

The objectives hierarchy, as defined by Buede, is the “hierarchy of objectives that are important to the system’s stakeholders in a value sense” (Buede 2009, 182). The objectives hierarchy does not imply physical characteristics or attributes that the system should contain. Instead, it helps to organize and prioritize requirements and goals of the system which will later be traced to physical characteristics. The objectives hierarchy was presented in Chapter 2 of this study and is presented again in Figure 12. The second presentation of the objectives hierarchy includes weighted values which will be used to develop the Value System Model later in this chapter.

The process for establishing the weighted values involved a careful look at the needs statement mentioned in Chapter 1, and at discussions and hierarchies from other reports, papers and stakeholders. A draft objectives hierarchy was created and presented to the stakeholders and project advisors. After receiving feedback, revisions were made and re-presented. The revision process occurred until the stakeholders and advisors were satisfied with the final weighted values presented in this thesis.

The weights shown in Figure 12 are shown in two different but related ways: local and global. Local weights are the representation of weights immediately under a category or subcategory. The total of weights under the immediate category or immediate subcategory sum to a total of 1.0. Global weights establish the relative importance of the item to the overall system. To obtain the global weight of each item, the product of the local weight and all parent local weights is calculated. By doing so, the total sum of all global weights at the lowest level equals 1.0. For clarity, when one value is given for a specific objective, this represents the local weight only. When two numbers are given, the left number is the local weight and the right number is the global weight.

The global weights shown in Figure 12 reflect the importance of each of the functions relative to the entire system. The figure shows that both operational effectiveness and suitability are of equal importance. Without each of these objectives being accomplished, it is difficult successfully meet the overall objective. Functions of supportability, survivability, reliability, and maintainability are not given weights for this exercise. It is important to note that these functions are important and should be investigated in further study and analysis. For this study, these functions are common among most satellite systems and are assumed to be significantly resembled in the SSP satellite architecture and design alternatives in this study.

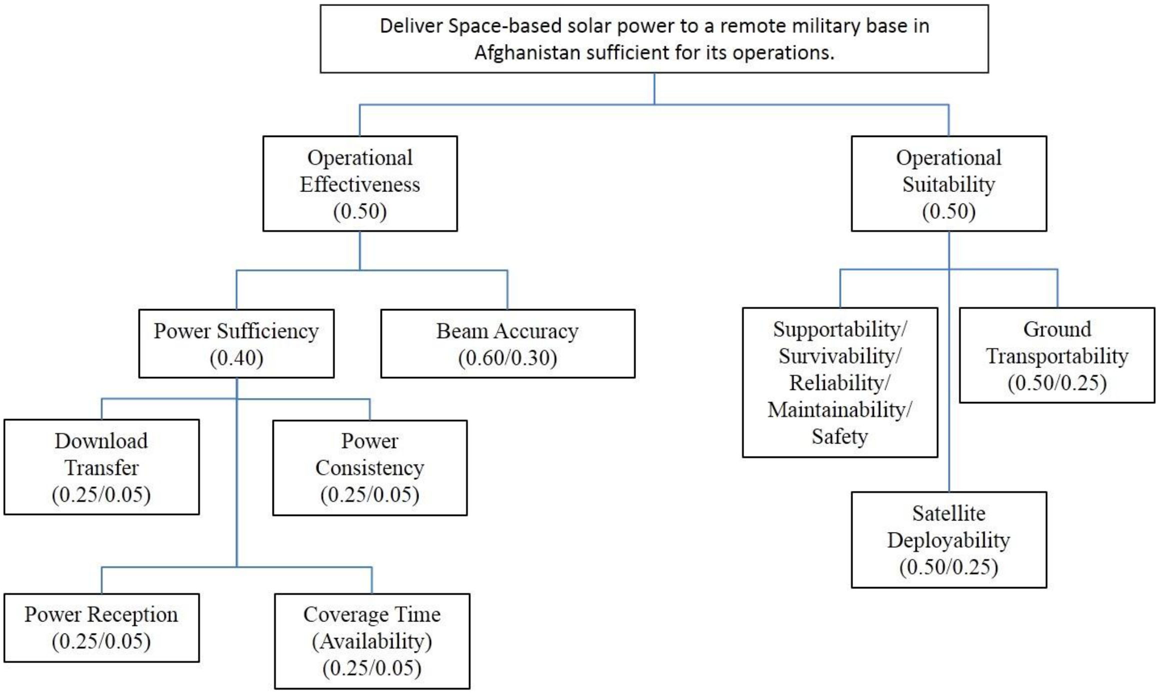


Figure 12. Objectives hierarchy with weights

2. Analysis Plan

The analysis begins by first compiling the values of the physical components for all design alternatives. One example would be the diameter of the transmitter. The values for each physical component are then scored relative to the other design alternatives for that same physical component and then weighted accordingly. The produced score for each physical component is used to calculate the overall Measure of Effective (MOE) for the system function and then the overall MOE for the system design alternative. The highest MOE of the three designs will determine which design alternative best fits the overall requirements of this thesis relative to the other design alternatives.

The goal of this research and analysis is to present one system architecture with three design alternatives to meet the given requirements and to choose which is the most effective among them. Three separate design alternatives are presented. The framework for the designs is based on the research as discussed in the Architecture and Design Attributes section below and the work of Raul Gómez et al.

3. Architecture and Design Attributes

This section discusses each of the major physical components, derived from the allocated architecture, and explains their Measure of Performance (MOP) attributes to be presented in each system design alternative to follow. Some components have multiple aspects requiring discussion. The goal of this section is to define the architecture attributes and design attributes that will both vary and be equal among design alternatives.

One attribute not directly related to a specific physical component is the orbit in which the satellite will operate. The architecture assumes a Geostationary (GEO) orbit as the optimal operating orbit. While in GEO, the solar powered satellite has the longest exposure time to the sun's rays, receiving optimal power from the sun. The time the satellite spends in eclipse is less than 70 minutes (Guoan 2006, 4), or approximately 5% of the orbital period (Wilder 2010, 56). An eclipse in GEO only occurs about twice per year and therefore the satellite would be shaded less than 1% of the total time. Because of the high percentage of availability, the proposed architecture pursues only one SSP satellite system. Additionally, very little beam steering is required as a result of the orbit and the axial tilt of the Earth with respect to the Sun (NSSO 2007, A-2).

The following is a discussion of each physical component and its function as derived from the allocated architecture. The result is the determination of each physical component's attributes, their functional MOP, and whether the value is equal across designs used in this study or if the functional MOP varies for each design. A summary of this discussion is found in Table 3.

Table 3. Summary of physical components, functional attributes, and design values

Physical Component	Attribute Name	Measurement	Design Value
Solar Panels	power per mass	W/kg	4,300 W/kg
	power per area solar flux	W/m^2	1,360 W/m^2
	efficiency (% loss)	% loss	73% loss
	useable time	% total time	99%
	mass of solar panels	kg	varies
	power received	MW	varies
Power Transmitter	transmission type	N/A	microwave
	frequency	GHz	38 GHz
	transmitter diameter	m	varies
	power transmitted	MW	varies
	mass of transmitter	kg	varies
Ground Power Receiver	rectenna diameter	m	varies
	power receivable (max)	MW	varies
	power received (actual)	MW	varies
	% power loss due to rectenna size	% loss	varies
Satellite Deployment System	payload max mass per launch vehicle	kg	13,400 kg
	mass of payload (transmitter + panels)	kg	varies
	# of launch vehicle payloads needed	#	varies
	orbit	N/A	GEO
Ground Deployment System	payload max mass per air vehicle	kg	122,472 kg
	# of air transport payload needed	#	varies

a. Solar Panels

The pertinent factors to SSP panels are size, weight, useable time, power received, and efficiency. The size to power relationship is measured as watts per square meter (W/m^2) of solar panel used. Two recent studies use 1360 W/m^2 (Gómez et al. 2009, 22) and 1,366 W/m^2 (NSSO 2007, 4). This study will assume the former of 1,360 W/m^2.

Mass is measured in comparison to watts and is presented as watts per kg (W/kg). Estimates of some solar power cells in space are approximately 50 to 80 w/kg (Rapp 2007, 4). Thin-film cell arrays provide estimates of upwards 1,000 W/kg (Hoffman 2002, 5) and even 4,300 W/kg (Gómez et al. 2009, 37). This thesis utilizes the most optimistic and assumes the 4,300 W/kg in order to meet desired power output with lowest satellite mass.

Efficiency of the solar panel is measured in the amount of power lost in the process of receiving and outputting the power to the transmitter. This is represented as the percentage loss (% loss) of power. Some technologies claim an efficiency loss as little as 4.6 %, but the lifetime of these solar cells is considered too short to be practical for the application of SSP (Bailey et al. 2002, 1). Other estimates are losses of 85% (ISU 1992, xxxix), 87% (Rapp 2007, 4), and 85% (Wilder 2010, 71) losses. Solar cells in development, such as multi-junction solar cells, claim to reach better results with typical losses of 75% (Luce 2002, 43), 73% (Rapp 2007, 34), and other cell types claiming 50% to 60% loss (NSSO 2007, 21). Due to the varying solar cell technologies reviewed and opinions of solar cell efficiencies, this study will assume solar panel energy loss of about 67%. Note that efficiency of Power Converter 1 is taken into account when calculating the overall solar panel efficiency loss in Table 3.

Lastly, useable time is important to determine how much power the solar power can collect. Useable time is dependent upon which orbit the satellite system is placed, which is assumed to be GEO for this research. Because the satellite is considered to be exposed to the sun over 99% of the time, this factor is considered negligible.

b. Power Converter—Direct Current (DC) to Radio Frequency (RF)

The first power converter examines conversion of the solar power received from the solar panel to the desired medium of transmission. The Power Transmitter section below explains the rationale for choosing a microwave methodology, and consequently the first power converter will convert DC to RF. Estimates show 60% (ISU 1992, xi) and greater than 80% (Gómez et al. 2009, 36) efficiencies when converting the power. This thesis assumes 80% efficiency for its architecture. The overall efficiency for receiving the solar power and converting it for transmission is about 27%, or given as a 73% loss in Table 3.

c. Direction Beam

The direction beam ensures that the beam accurately targets the rectenna so that maximum power can be captured and used. The direction beam is especially important for laser transmission concepts due to its technological safety concerns. A goal of the direction beam would be to limit the beam from targeting unintended locations. As the next section explains, microwave power is believed to be less a threat than laser concepts to humans and the atmosphere, but further testing still needs to be done to verify this. If tests show that either laser or microwave transmission can be detrimental, the control mechanism for the beam ought to have an extremely high accuracy rate with several automatic safety systems onboard. Donald Rapp proposes, “the center of the microwave beam should be confined to a region within 0.0005 degrees of the center of the rectenna” (Rapp 2007, 32). As the following designs propose, the mass of these satellite systems is extremely large by comparison to most space systems in existence, and therefore any disruption of normal operations causing the slightest movement may have catastrophic effects. While this is an extremely important component of the system architecture, further research needs to be conducted to ensure its accuracy and safety. This study assumes that all designs would use the same direction beam mechanism and assumes an error rate negligible to this research.

d. Power Transmitter

There are several important factors when considering power transmission for the systems architecture and design. The first consideration is the type of transmission. In doing research, the majority of sources reviewed have weighed the benefits and faults of microwave and laser transmission. Potential laser concepts have efficiencies near 20%, which means approximately 80% of the heat must be managed by equipment on the satellite (Gómez et al. 2009, 26). In contrast, researched microwave power is believed to achieve near 76% efficiencies (Brown 1992, 1240) with some claims upwards of 94% to near 100% (Gómez et al. 2009, 27, 30). Drawbacks to laser transmission are adverse beam affects when traveling through clouds and particular weather (Gómez et al. 2009, 38) whereas microwave transmission is not affected at all.

Laser transmission is also disrupted by atmospheric turbulence near the ground (Wilder 2010, 27). Although the larger community may be skeptical, it is believed by some that microwave transmission is safe for birds and aircraft to fly through it (Wood 2012, 71). The larger community affirms that microwave transmission has the overall edge and is therefore used in all design alternatives presented in this study. As for the efficiency of the microwave beam, the high efficiency projections by Gómez et al. conclude this area to be negligible for this research. Rather, the consideration of rectenna size in the next section has a greater impact on the percentage of transmitted power received and is of greater interest in building the system designs. The amount of power transmitted will be determined in each design alternative.

A second power transmission consideration is the optimal frequency for transmission. Research indicates that the two frequency ranges of 2.4 to 5.4 GHz and 35 to 38 GHz have been considered as optimal. All else equal, studies and research show that 2.45 GHz transmission requires a significant increase in rectenna size and overall cost (Gómez et al. 2009, 65) with an estimate by the NSSO stating the rectenna is two hundred times larger in area when compared to using a transmission frequency of 35 to 38 GHz. Additionally, the NSSO states the ionosphere is heated two hundred times more at 2.45 GHz compared to 35 GHz and can potentially interfere with mobile phones, which also use the 2.45 GHz spectrum (ISU 1992, xxxix). Because a large amount of literature points to the 35 to 38 GHz spectrum, this thesis will utilize the 38 GHz spectrum since this allows transmission of the most energy into the smallest space and is best for operational purposes to a remote military base.

The last three areas to consider for power transmission are the size of the transmitter, the mass of the transmitter, and the amount of power transmitted. The size is measured by its diameter and is given in meters. The mass of the transmitter is measured in kilograms. Power transmitted is measured in megawatts (MW) and is driven primarily by the power received from the solar panels. All three areas will be determined in each design alternative.

e. Ground Power Receiver (Rectenna)

The ground power receiver is a rectified antenna, referred to as the rectenna, and three related attributes are considered for the systems architecture. The first consideration is the area of the rectenna and is measured by its diameter in meters squared (m^2). The second is the amount of power received, measured in MW. The power released by the rectenna takes into consideration the rectenna size, the microwave transmission, the size of the microwave beam, which is determined by the size of the transmitter, and the power density of the beam. As mentioned earlier, a larger transmitter creates a more focused microwave beam, requiring a smaller rectenna to receive the maximum power from the beam. Area of the rectenna and the amount of power received will vary for each design alternative. The third attribute is efficiency of the rectenna and is discussed as part of the second power converter below.

f. Power Converter 2—RF to DC

The second power converter is located on the ground as part of the rectenna and converts the received RF back to DC before output to the user. The overall efficiency of both the rectenna and the power are considered to be extremely high. If designed correctly, the rectenna can achieve near perfect conversion from RF to DC (Gómez et al. 2009, 30) and is therefore considered negligible for this study.

g. Satellite Deployment System

The primary area of consideration of the satellite deployment system is the launch vehicle. The payload’s maximum weight is determined by the vehicle and its configuration. Three launch vehicles in their respective weight carrying configurations were examined: United Launch Alliance’s Atlas V and Delta IV, and Space X’s Falcon 9H. The maximum payload weight for the Atlas V 521 to Geosynchronous Transfer Orbit (GTO) is about 9,000 kg (Lockheed Martin 1999, 2–30). For Delta IV Heavy, the maximum weight is about 13,400 kg to GTO (ULA 2007, 2–10). Space X’s Falcon 9H can carry a payload to GEO of approximately 11,500 kg (Gómez et al. 2009, 33). This study assumes these maximum capacities available for a SSP launch and uses the Delta IV Heavy’s 13,400 kg standard in the system architecture. The payload mass will be approximated in each of the design alternatives. Knowing the total payload mass and maximum mass per vehicle, the number of launch vehicles needed will be calculated for each design alternative.

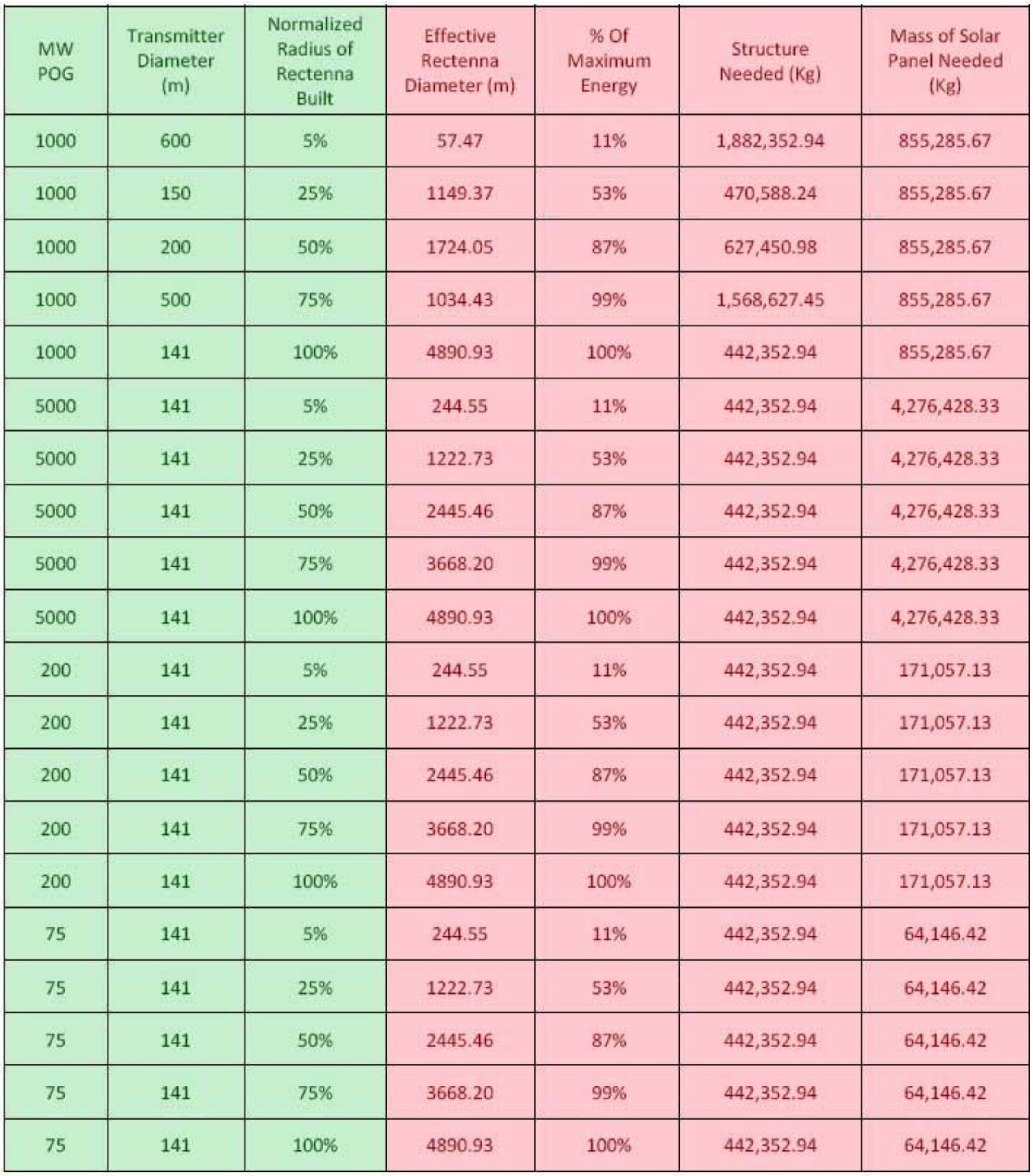
h. Ground Deployment System

The ground deployment system is primarily concerned with how to get the rectenna to the destination in Afghanistan. This is determined by utilizing the largest available cargo plane to the U.S military, the Air Force's C-5 Galaxy. The maximum payload capacity is designed at 122,472 kg (USAF 2012), which is the value used for this study. With this given capacity load and the mass of the rectenna system, the approximate number of flights needed to transport the rectenna system will be calculated for each of the architectures.

4. Proposed Design Alternatives

The following design alternatives are based on the discussion of architecture attributes above and the sample SSP system technical models from Raul Gómez et al. Given various MW outputs, Gómez calculates the needed rectenna diameter, the percentage of energy received, and mass of solar panels. Gómez's assumptions in calculating his models align with the assumptions made in this research. His sample technical calculations can be found in Table 4 and help to fill in the areas where the Value in Table 3 reads "varies" for a particular value. Table 4 is a snapshot of the pertinent calculations from Gómez and excludes irrelevant data from his original table. The value in the first column of Table 4, power on ground (POG), refers to the power which hits the ground, not the power actually received by the rectenna.

Table 4. Sample technical model calculations (from Gómez et al. 2009, L)



MW POG	Transmitter Diameter (m)	Normalized Radius of Rectenna Built	Effective Rectenna Diameter (m)	% Of Maximum Energy	Structure Needed (Kg)	Mass of Solar Panel Needed (Kg)
1000	600	5%	57.47	11%	1,882,352.94	855,285.67
1000	150	25%	1149.37	53%	470,588.24	855,285.67
1000	200	50%	1724.05	87%	627,450.98	855,285.67
1000	500	75%	1034.43	99%	1,568,627.45	855,285.67
1000	141	100%	4890.93	100%	442,352.94	855,285.67
5000	141	5%	244.55	11%	442,352.94	4,276,428.33
5000	141	25%	1222.73	53%	442,352.94	4,276,428.33
5000	141	50%	2445.46	87%	442,352.94	4,276,428.33
5000	141	75%	3668.20	99%	442,352.94	4,276,428.33
5000	141	100%	4890.93	100%	442,352.94	4,276,428.33
200	141	5%	244.55	11%	442,352.94	171,057.13
200	141	25%	1222.73	53%	442,352.94	171,057.13
200	141	50%	2445.46	87%	442,352.94	171,057.13
200	141	75%	3668.20	99%	442,352.94	171,057.13
200	141	100%	4890.93	100%	442,352.94	171,057.13
75	141	5%	244.55	11%	442,352.94	64,146.42
75	141	25%	1222.73	53%	442,352.94	64,146.42
75	141	50%	2445.46	87%	442,352.94	64,146.42
75	141	75%	3668.20	99%	442,352.94	64,146.42
75	141	100%	4890.93	100%	442,352.94	64,146.42

The following design alternatives utilize the assumed attributes presented in Table 3 and the variable attributes calculated by Gómez et al. in Table 4. The architectures are created to best meet the power requirement as defined in Chapter II of this thesis. Taking the MW POG and the Percentage of Maximum Energy from Table 4, three solutions were determined to best meet this study's requirements. Three design alternatives are presented - Architectures A, B, and C - and all seek to meet the 45 MW to 135 MW requirement. Attributes of all three design alternatives are summarized in Table 5.

a. Design Alternative A

Design alternative A seeks to meet the power requirement between 45 MW and 135 MW. The mass of the solar panels is given as 855,285.67 kg with a 600 m diameter transmitter in order to output 1,000 MW at the transmitter. The rectenna has a diameter of 57.47m and receives 110 MW of power. The mass of the total launch vehicle payload is 2,737,638.61 kg and requires an estimated 204.3 payloads. The total mass to be transported to the remote military base is 1,882,352.94 kg and requires an estimated 15.37 vehicles. The design alternative attributes are presented in Table 5 below.

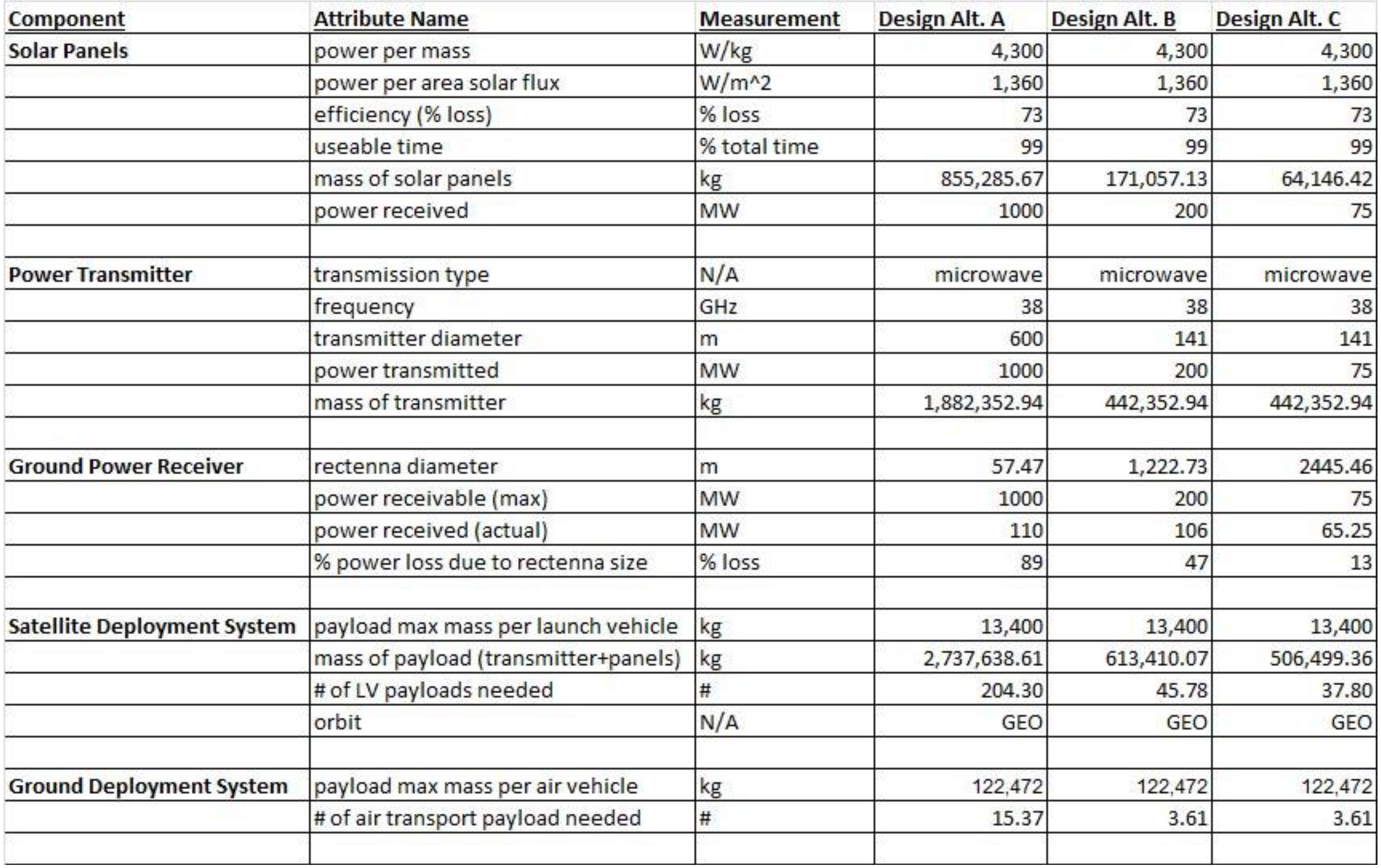
b. Design Alternative B

Design alternative B seeks to meet the power requirement between 45 MW and 135 MW. The mass of the solar panels is given as 171,057.13 kg with a 141 m diameter transmitter in order to output 200 MW at the transmitter. The rectenna has a diameter of 1222.73 m and receives 106 MW of power. The mass of the total launch vehicle payload is 613,410.07 kg and requires an estimated 45.78 payloads. The total mass to be transported to the remote military base is 442,352.94 kg and requires an estimated 3.61 vehicles. The design alternative attributes are presented in Table 5 below.

c. Design Alternative C

Design alternative C seeks to meet the power requirement between 45 MW and 135 MW. The mass of the solar panels is given as 64,146.42 kg with a 141 m diameter transmitter in order to output 75 MW at the transmitter. The rectenna has a diameter of 2,445.46 m and receives 65.25 MW of power. The mass of the total launch vehicle payload is 506,499.36 kg and requires an estimated 37.8 payloads. The total mass to be transported to the remote military base is 442,352.94 kg and requires an estimated 3.61 vehicles. The design alternative attributes are presented in Table 5 below

Table 5. Summary of design alternatives



Component	Attribute Name	Measurement	Design Alt. A	Design Alt. B	Design Alt. C
Solar Panels	power per mass	W/kg	4,300	4,300	4,300
	power per area solar flux	W/m^2	1,360	1,360	1,360
	efficiency (% loss)	% loss	73	73	73
	useable time	% total time	99	99	99
	mass of solar panels	kg	855,285.67	171,057.13	64,146.42
	power received	MW	1000	200	75
Power Transmitter	transmission type	N/A	microwave	microwave	microwave
	frequency	GHz	38	38	38
	transmitter diameter	m	600	141	141
	power transmitted	MW	1000	200	75
	mass of transmitter	kg	1,882,352.94	442,352.94	442,352.94
Ground Power Receiver	rectenna diameter	m	57.47	1,222.73	2445.46
	power receivable (max)	MW	1000	200	75
	power received (actual)	MW	110	106	65.25
	% power loss due to rectenna size	% loss	89	47	13
Satellite Deployment System	payload max mass per launch vehicle	kg	13,400	13,400	13,400
	mass of payload (transmitter+panels)	kg	2,737,638.61	613,410.07	506,499.36
	# of LV payloads needed	#	204.30	45.78	37.80
	orbit	N/A	GEO	GEO	GEO
Ground Deployment System	payload max mass per air vehicle	kg	122,472	122,472	122,472
	# of air transport payload needed	#	15.37	3.61	3.61

5. Evaluation Measures and Weighting

The evaluation method for each component is based on the discussion in the Architecture and Design Attributes section of this study. A summary of the architecture and design attributes and their measurements is summarized in Table 5.

To determine the system weighted values for each component, this thesis uses a three step House of Quality process. House of Quality 1 begins with the Objectives Hierarchy and its determined weights as presented in Figure 12. The objectives are paired and evaluated against their relation and importance to the requirements, producing a weighted performance for the requirements. The following scoring system was determined by the stakeholders and project advisor and the score was determined by the thesis student. An evaluation score of "0" means no importance and no relation. An evaluation score of "3" means little importance and little relation. A score of "9" means high importance and high relation. House of Quality 2 pairs and evaluates the weighted requirements from House of Quality 1 against the functions as determined earlier in this study. The same evaluation criteria in House of Quality 1 are used and the result is a weighted performance for each function. In House of Quality 3, the weighted values of each function from House of Quality 2 is paired and evaluated against the physical components as determined in the Allocated Architecture section of this study. The same evaluation criteria in House of Quality 1 are used. House of Quality 3 produces a weighted measure for each physical component. Houses of Quality 1 through 3 and their respected evaluations are presented in Tables 6 through 8, respectfully.

Table 6. House of quality 1: objectives evaluated against requirements

			Requirements						
			Provide Power	Utilize Space-Based Solar Power	Support Remote Bases in Afghanistan	Gapless Power Support	Ground Transportability	Space Deployability	
Objectives	*Weights*		MW	days		time	Units	Units	
Power Reception	0.05	0.050	**9**	**3**	**3**				
Download/Transfer of Power	0.05	0.050	**9**	**3**	**3**				
Power Consistency	0.05	0.050	**3**			**9**			
Coverage Time (Availability)	0.05	0.050	**3**	**3**		**9**			
Beam Accuracy	0.3	0.300				**9**		**3**	
Satellite Deployability	0.25	0.250						**9**	
Ground Transportability	0.25	0.250					**9**		
Check Sum		1.00							
Weighted Performance			1.2	0.5	0.3	3.6	2.3	3.2	11.0
Percent Performance			0.110	0.041	0.027	0.329	0.205	0.288	

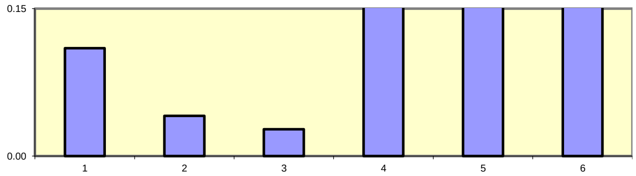


Table 7. House of quality 2: requirements evaluated against functions

			Functions (Hows)											
			Satellite System				Ground System			Support System				
			A1: Receive Solar Power	A2: Convert to Transmittable Power	A3: Direct Beam	A4: Transmit Power	A5: Receive Power	A6: Convert to Standard Power	A7: Manage and Disburse Power	A8: Deploy from Earth to Space	A9: Transport to Designated Location in Space	A10: Manage Power, Support and Maintenance Systems	A11: Deploy Ground System	
Requirements	Weights		MW	MW		MW	MW	MW		Units	Units	Units	Units	
Provide Power	0.110	0.110	9	9	9	9	9	9	9					
Utilize Space-Based Solar Power	0.041	0.041	3	3		9	9							
Support Remote Bases in Afghanistan	0.027	0.027			9	3	3				9		9	
Gapless Power Support	0.329	0.329				9						9		
Ground Transportability	0.205	0.205											9	
Space Deployability	0.288	0.288								9	9			
Check Sum		1.00												
Weighted Performance			1.1	1.1	1.2	4.4	1.4	1.0	1.0	2.6	2.8	3.0	2.1	21.7
Percent Performance			0.051	0.051	0.057	0.202	0.066	0.045	0.045	0.119	0.130	0.136	0.096	

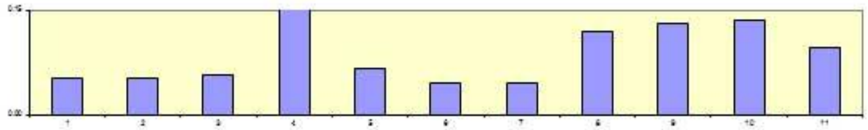
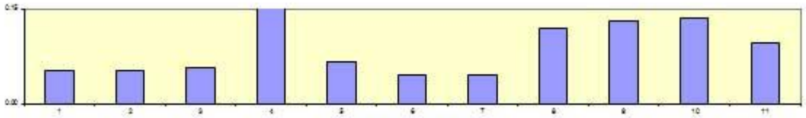


Table 8. House of quality 3: functions evaluated against physical components

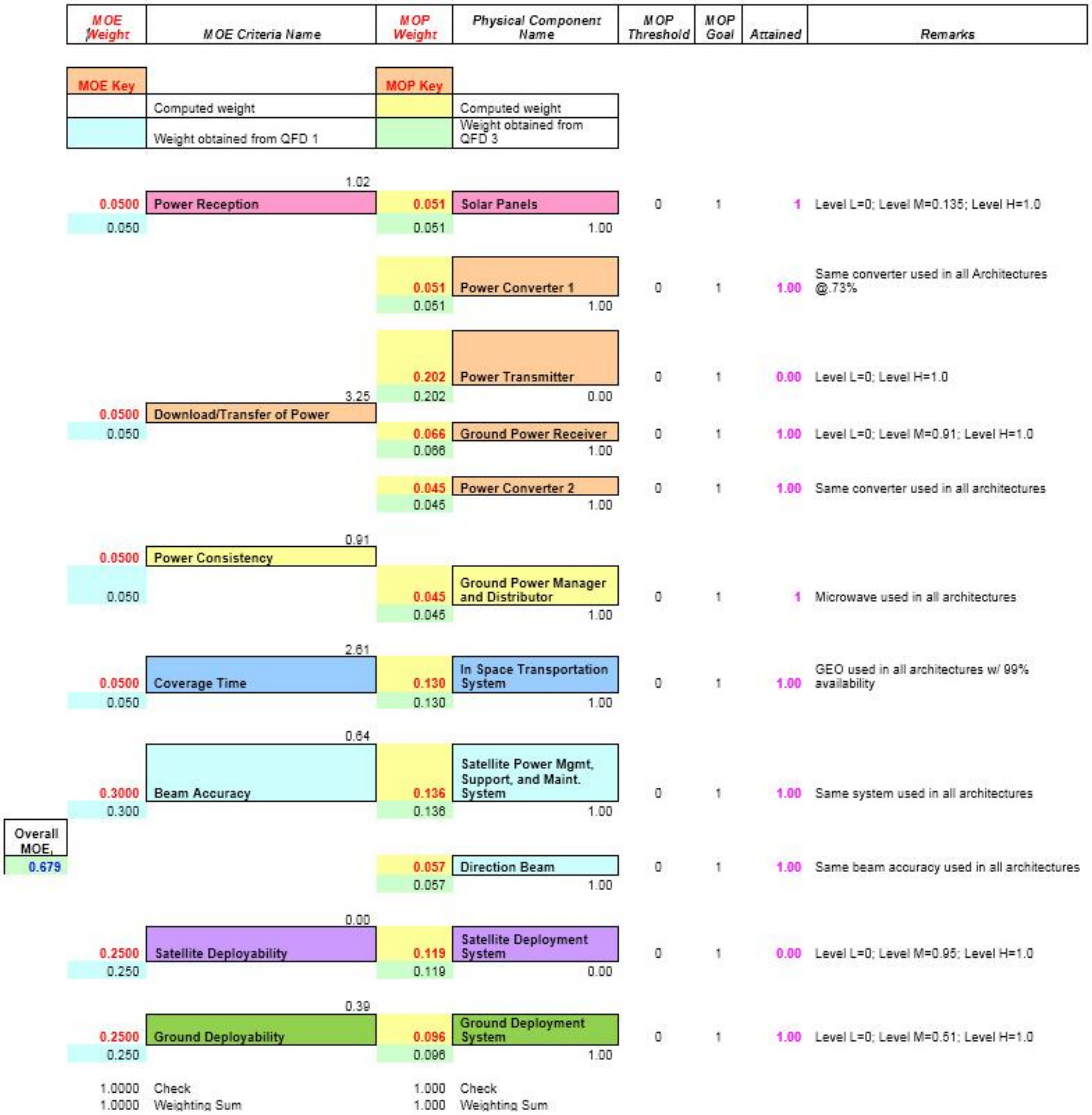
Functions (Whats)	Weights		Physical Components: Solar Panels	Power Converter 1	Direction Beam	Power Transmitter	Ground Power Receiver	Power Converter 2	Ground Power Manager and Distributor	Satellite Deployment System	In-Space Transportation System	Satellite Power Mgmt, Support, and Maint. System	Ground Deployment System	
			kw	% loss	% accurate	type	MW	% loss		Units			Units	
A1: Receive Solar Power	0.051	0.051	9											
A2: Convert to Transmittable Power	0.051	0.051		9										
A3: Direct Beam	0.057	0.057			9									
A4: Transmit Power	0.202	0.202				9								
A5: Receive Power	0.066	0.066					9							
A6: Convert to Standard Power	0.045	0.045						9						
A7: Manage and Disburse Power	0.045	0.045							9					
A8: Deploy from Earth to Space	0.119	0.119								9				
A9: Transport to Designated Location in Space	0.130	0.130									9			
A10: Manage Power, Support and Maintenance Systems	0.136	0.136										9		
A11: Deploy Ground System	0.096	0.096											9	
Check Sum		1.00												
Weighted Performance			0.5	0.5	0.5	1.8	0.6	0.4	0.4	1.1	1.2	1.2	0.9	9.0
Percent Performance			0.051	0.051	0.057	0.202	0.066	0.045	0.045	0.119	0.130	0.136	0.096	



6. Value System Modeling

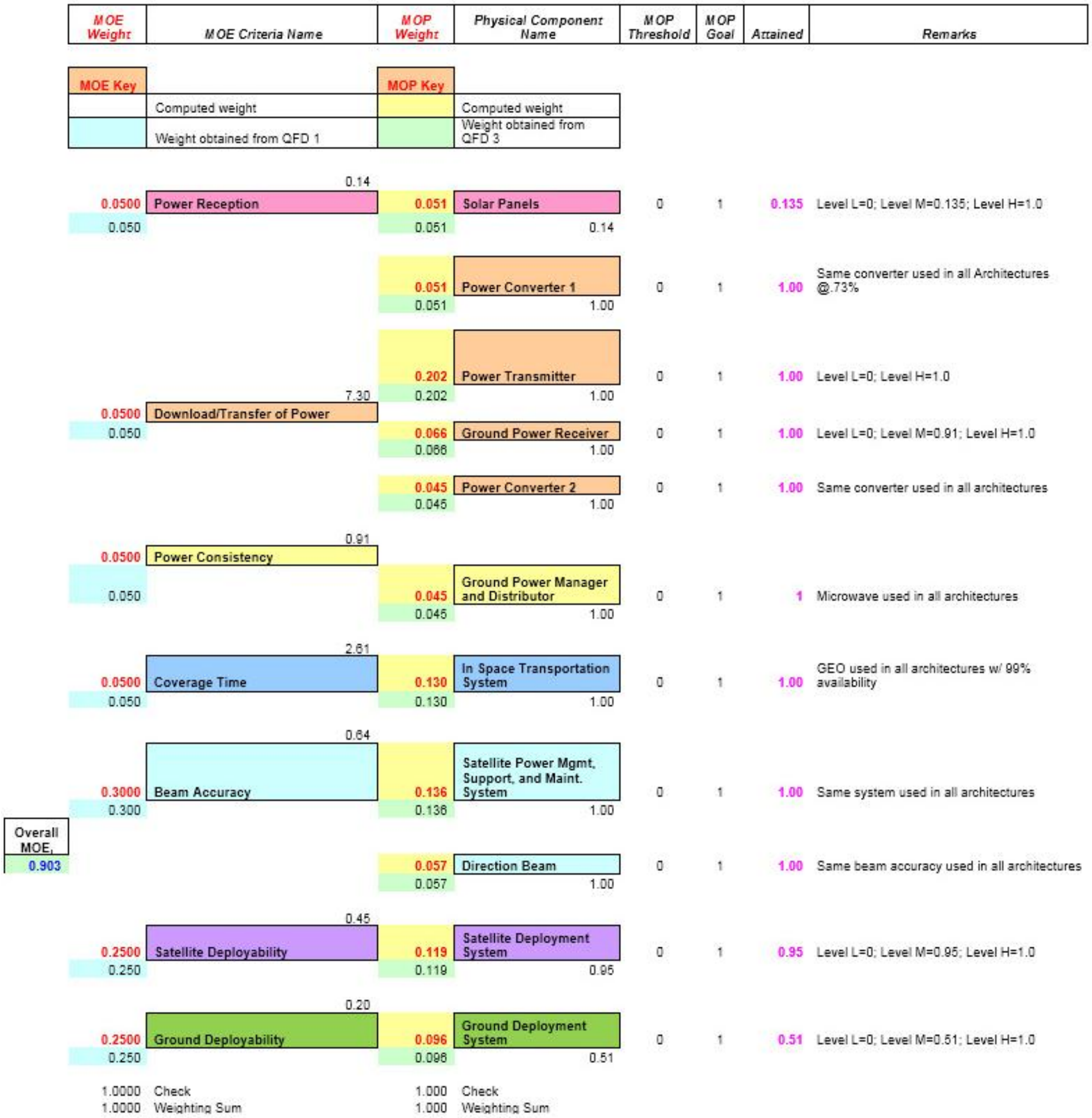
The Value System Model utilizes the weighted measures obtained in the Houses of Quality and applies the actual attained values presented in the system design alternatives. A complement aspect of the objectives hierarchy and the Houses of Quality process is measures of effectiveness (MOE) scoring. MOE scores describe “how well a system carries out a task or a set of tasks within a specific context; an MOE is measured outside the system for a defined environment and state of the context variables and is used to define mission requirements” (Buede 2009, 182). Each physical component has a corresponding functional Measure of Performance (MOP), MOP threshold, MOP Goal, and Attained Value. A score of 0 to 1 is given based on how well the attained value meets the MOP threshold and goal. For this thesis, all Attained Values are evaluated relative to the three design alternatives presented. This is the case for all MOP Attributes except the ground power receiver, which is given a score of 1 if the design alternative meets the 45 MW to 135 MW requirement and is given a score of 0 if the design alternative does not. Once all Attained Values are found, the individual score is then multiplied by the corresponding component weighted value as determined in House of Quality 3 to produce a MOP score. By adding all MOP scores for a particular function, and then multiplying it against the weighted function score from the Objectives Hierarchy with weights, each function receives an MOE score. The total of all function MOE scores produce an overall system design MOE score. A summary of the physical component MOP, MOP threshold, MOP goal, Attained MOP Value and overall MOE score for Architectures A through C is presented in the System Value Models in Tables 9 through 11, respectfully.

Table 9. System value model: design alternative A



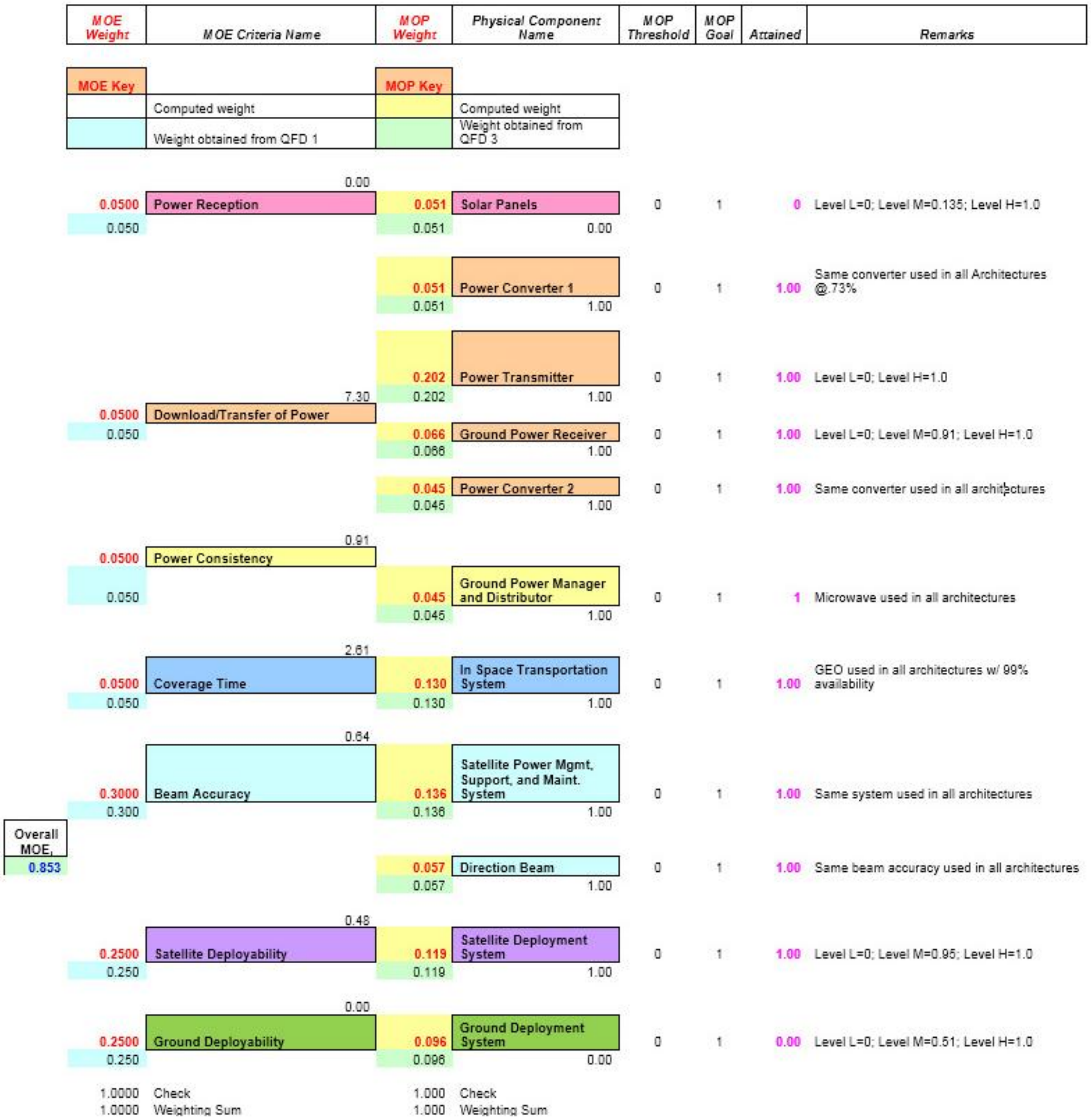
MOE Weight	MOE Criteria Name	MOP Weight	Physical Component Name	MOP Threshold	MOP Goal	Attained	Remarks
MOE Key		MOP Key					
	Computed weight		Computed weight				
	Weight obtained from QFD 1		Weight obtained from QFD 3				
0.0500 0.050	1.02 Power Reception	0.051 0.051	Solar Panels 1.00	0	1	1	Level L=0; Level M=0.135; Level H=1.0
		0.051 0.051	Power Converter 1 1.00	0	1	1.00	Same converter used in all Architectures @.73%
		0.202 0.202	Power Transmitter 0.00	0	1	0.00	Level L=0; Level H=1.0
0.0500 0.050	3.25 Download/Transfer of Power	0.066 0.066	Ground Power Receiver 1.00	0	1	1.00	Level L=0; Level M=0.91; Level H=1.0
		0.045 0.045	Power Converter 2 1.00	0	1	1.00	Same converter used in all architectures
0.0500 0.050	0.91 Power Consistency	0.045 0.045	Ground Power Manager and Distributor 1.00	0	1	1	Microwave used in all architectures
0.0500 0.050	2.61 Coverage Time	0.130 0.130	In Space Transportation System 1.00	0	1	1.00	GEO used in all architectures w/ 99% availability
0.3000 0.300	0.64 Beam Accuracy	0.136 0.136	Satellite Power Mgmt, Support, and Maint. System 1.00	0	1	1.00	Same system used in all architectures
Overall MOE, 0.679		0.057 0.057	Direction Beam 1.00	0	1	1.00	Same beam accuracy used in all architectures
0.2500 0.250	0.00 Satellite Deployability	0.119 0.119	Satellite Deployment System 0.00	0	1	0.00	Level L=0; Level M=0.95; Level H=1.0
0.2500 0.250	0.39 Ground Deployability	0.096 0.096	Ground Deployment System 1.00	0	1	1.00	Level L=0; Level M=0.51; Level H=1.0
1.0000	Check	1.000	Check				
1.0000	Weighting Sum	1.000	Weighting Sum				

Table 10. System value model: design alternative B



MOE Weight	MOE Criteria Name	MOP Weight	Physical Component Name	MOP Threshold	MOP Goal	Attained	Remarks
MOE Key		MOP Key					
⬜	Computed weight	🟨	Computed weight				
🟦	Weight obtained from QFD 1	🟩	Weight obtained from QFD 3				
0.0500 0.050	0.14 Power Reception	0.051 0.051	Solar Panels 0.14	0	1	0.135	Level L=0; Level M=0.135; Level H=1.0
		0.051 0.051	Power Converter 1 1.00	0	1	1.00	Same converter used in all Architectures @.73%
		0.202 0.202	Power Transmitter 1.00	0	1	1.00	Level L=0; Level H=1.0
0.0500 0.050	7.30 Download/Transfer of Power	0.066 0.066	Ground Power Receiver 1.00	0	1	1.00	Level L=0; Level M=0.91; Level H=1.0
		0.045 0.045	Power Converter 2 1.00	0	1	1.00	Same converter used in all architectures
0.0500 0.050	0.91 Power Consistency	0.045 0.045	Ground Power Manager and Distributor 1.00	0	1	1	Microwave used in all architectures
0.0500 0.050	2.61 Coverage Time	0.130 0.130	In Space Transportation System 1.00	0	1	1.00	GEO used in all architectures w/ 99% availability
0.3000 0.300	0.64 Beam Accuracy	0.136 0.136	Satellite Power Mgmt, Support, and Maint. System 1.00	0	1	1.00	Same system used in all architectures
Overall MOE, 0.903		0.057 0.057	Direction Beam 1.00	0	1	1.00	Same beam accuracy used in all architectures
0.2500 0.250	0.45 Satellite Deployability	0.119 0.119	Satellite Deployment System 0.95	0	1	0.95	Level L=0; Level M=0.95; Level H=1.0
0.2500 0.250	0.20 Ground Deployability	0.096 0.096	Ground Deployment System 0.51	0	1	0.51	Level L=0; Level M=0.51; Level H=1.0
1.0000 1.0000	Check Weighting Sum	1.000 1.000	Check Weighting Sum				

Table 11. System value model: design alternative C



	MOE Weight	MOE Criteria Name	MOP Weight	Physical Component Name	MOP Threshold	MOP Goal	Attained	Remarks
	MOE Key		MOP Key					
		Computed weight		Computed weight				
		Weight obtained from QFD 1		Weight obtained from QFD 3				
		0.00						
	0.0500	Power Reception	0.051	Solar Panels	0	1	0	Level L=0; Level M=0.135; Level H=1.0
	0.050		0.051	0.00				
			0.051	Power Converter 1	0	1	1.00	Same converter used in all Architectures @.73%
			0.051	1.00				
			0.202	Power Transmitter	0	1	1.00	Level L=0; Level H=1.0
		7.30	0.202	1.00				
	0.0500	Download/Transfer of Power						
	0.050		0.066	Ground Power Receiver	0	1	1.00	Level L=0; Level M=0.91; Level H=1.0
			0.066	1.00				
			0.045	Power Converter 2	0	1	1.00	Same converter used in all architectures
			0.045	1.00				
		0.91						
	0.0500	Power Consistency						
	0.050		0.045	Ground Power Manager and Distributor	0	1	1	Microwave used in all architectures
			0.045	1.00				
		2.61						
	0.0500	Coverage Time	0.130	In Space Transportation System	0	1	1.00	GEO used in all architectures w/ 99% availability
	0.050		0.130	1.00				
		0.64						
	0.3000	Beam Accuracy	0.136	Satellite Power Mgmt, Support, and Maint. System	0	1	1.00	Same system used in all architectures
	0.300		0.136	1.00				
Overall MOE, 0.853			0.057	Direction Beam	0	1	1.00	Same beam accuracy used in all architectures
			0.057	1.00				
		0.48						
	0.2500	Satellite Deployability	0.119	Satellite Deployment System	0	1	1.00	Level L=0; Level M=0.95; Level H=1.0
	0.250		0.119	1.00				
		0.00						
	0.2500	Ground Deployability	0.096	Ground Deployment System	0	1	0.00	Level L=0; Level M=0.51; Level H=1.0
	0.250		0.096	0.00				
	1.0000	Check	1.000	Check				
	1.0000	Weighting Sum	1.000	Weighting Sum				

7. Cost Analysis

Actual cost data for a SSP system is unknown, yet different estimates have been projected. One estimate is for base development costs of an SSP, which Gómez estimates at $132B USD, while the ESA estimates $265B USD (Gómez et al. 2009, 60, L). For production and expected total costs of the three designs used in this research, Gómez estimates a production cost of $1.58B USD and a total cost of $10.38B USD for Design Alternative A, a production cost of $356M USD and a total cost of $2.38B USD for Design Alternative B, and a production cost of $294M USD and a total cost of $2.13B USD for Design Alternative C (Gómez et al. 2009, 60, L). These estimates are for production costs for the expected system lifespan of 30 years, but they do not include maintenance costs.

A cost-value analysis was conducted by considering the design alternative MOE scores against their respected estimated costs and is shown in Table 12. By plotting this information in Figure 13, relationships can be seen between cost and effectiveness. In the case that one design alternative has a higher cost and a lower MOE score than another alternative, it is considered “dominated” by the other alternative. In this cost-value comparison, Alternative A is dominated by both Alternatives B and C because both have higher MOE scores and both have a lower cost. By conclusion, Alternative A would not be considered further.

Table 12. Design alternative cost versus MOE score

Design Alternative	**Estimated Total Cost (U.S. $ in billions)**	**MOE Score**
Design Alternative A	10.38	0.679
Design Alternative B	2.38	0.903
Design Alternative C	2.13	0.853

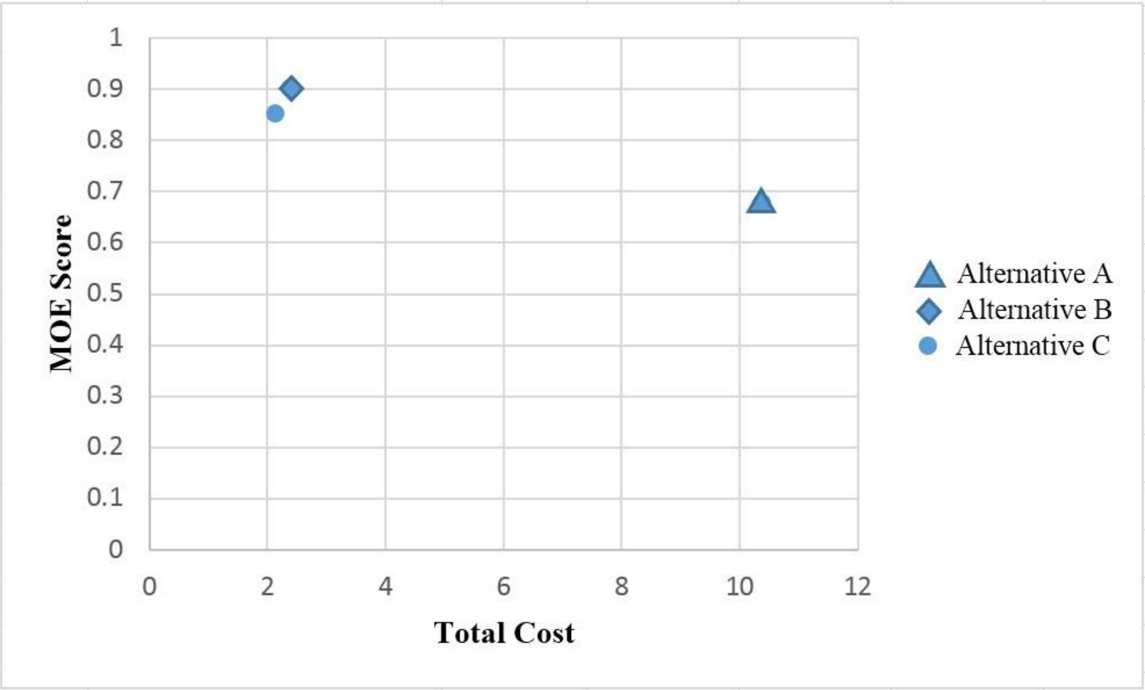


Figure 13. Design alternative total cost versus MOE score comparison

In order to select the better of the two remaining alternative designs with respect to cost, additional research and stakeholder involvement is required to determine the weight and importance of cost. Depending on the weight of the cost factor as defined by the stakeholder, Alternative A or B may be determined as the overall better alternative. If cost is not considered a significant factor, Alternative B will remain the overall better alternative due to having the higher of the MOE scores.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY OF FINDINGS

The research and conclusions within this study are targeted at finding the best systems design alternative for using SSP for military bases in Afghanistan where energy is expensive and/or very difficult to obtain. A review was conducted of literature concerning the need for renewable energy for the DoD, especially abroad in remote areas like Afghanistan. Additionally, research was conducted on key concepts and components necessary for SSP. One architecture with three system design alternatives were created and systematically weighed according to stakeholder requirements to determine which design best fit the user requirements.

B. FINAL CONCLUSIONS

The conclusion to the research and analysis is that a system architecture does exist and the best design alternative from the three examined by this thesis is presented in Design Alternative B. This design presents the most balanced approach and overall best meets the requirements relative to Design Alternatives A and C. Design Alternative B delivers 106 MW, which is well within the requirement, while maintaining a balanced approach to solar panel mass, transmitter size, rectenna size, and deployability of the entire system.

Design Alternative A falls short of being the best design due to having the largest satellite mass. The design consisted of the largest array of solar panels by a considerable amount. In addition, the mass of the transmitter is considerably more than the other designs as well. Both solar panel and transmitter mass result in the design requiring the most number of launches for operation and therefore decreases the satellite deployability score significantly. The benefit with Design Alternative A is the ability to use the smallest rectenna while maintaining the required power amount. If the maximum payload mass per launch can increase in future launch capability, Design Alternative A becomes a more reasonable solution.

Design Alternative C falls short of the best design due to it having the largest rectenna diameter at 2,445.46 meters. This is approximately twice the rectenna size of Design Alternative B and 42.5 times larger than Design Alternative A. This is impractical for use in a remote military base where space may be limited due to safety and security concerns. The strength of this architecture is that it requires fewest launches to space. In order to reduce the rectenna size, increasing either the number of solar panels or the size of the transmitter would be required, but this would result in increased launches required. While this design presents a solution with the least amount of mass deployed to space, the limit to ground deployability renders this design second best of the three.

Considering cost, Design Alternative A is not an option due to being “dominated” by the other alternatives having fewer total costs and higher overall MOE scores. Additional stakeholder analysis is required in order to determine how cost may affect the MOE scores of the other two alternatives. Depending on stakeholder analysis pertaining to cost, Alternative C could potentially be more effective than Alternative B.

While this study determined the best design alternative of the three presented, this study makes several assumptions. The first assumption, based on research and findings, is that the technology needed for SSP already exists and the system is technically feasible. The second assumption in this thesis is that SSP is the best alternative for meeting the power requirement.

C. RECOMMENDED AREAS OF FURTHER STUDY

While this thesis provides a look at the overall system architecture and design for the major components of a SSP satellite system, further areas of research will serve to benefit the concept. One area is to provide additional design alternatives and to re-calculate the overall MOEs relative to the other designs. This would provide a more robust data set. A further area would be to create additional architectures that have the same output of power but with varying values for the other factors. An example is to examine the lunar solar power concept, its corresponding architecture, and its operational suitability for providing power to a remote military base. This would require a greater focus on system availability and system components such as large capacity batteries and power management. Such a concept may lead to an architectural approach using both SSP satellites and fossil fuels. One technical area of further study includes the look at causes and effects of beam jitter in the space environment. A closer look is needed at the safety concerns and effects of proposed microwave power beam concepts. Another area of further research is to look at maintainability costs, and to receive stakeholder involvement for in-depth cost analysis to include in Design Alternative MOE scores. A detailed look at the extremely high cost of this system would be beneficial. Finally, a look into FOBs and their power consumption may significantly reduce the power requirement for a SSP system.

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