New Developments in Space Solar Power

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ABSTRACT

In December 2015, the great majority of Earth's nations, recognizing the urgent need to mitigate the looming risks of climate change, announced ambitious goals for the reduction of CO_2 emissions this century. At the same time, global demand for energy continues to expand with increasing populations and the need for improved economic conditions in all countries. In the judgment of many experts, these potentially-conflicting goals are unlikely to be accomplished solely through the use of already-existing technologies (such as hydro, terrestrial solar and wind power). Among other important options, Space Solar Power (SSP) remains one of the most-promising, but as yet largely undeveloped options to accomplish this goal.

During 2008-2011, the International Academy of Astronautics (IAA) accomplished the First International Assessment of Space Solar Power, involving diverse subject matter experts from some ten (10) countries. The IAA assessment found that SSP is technically feasible and that it might be realized in as little as 10-15 years. Following on those results, in 2011-2012 an international team, working under the auspices of NASA's Innovative Advanced Concepts (NIAC) program examined a novel, more practical hyper-modular approach to realizing SSP: "SPS-ALPHA" (Solar Power Satellite by means of Arbitrarily Large Phased Array), invented by the author. Together, the IAA and NIAC studies framed the foundation of an integrated treatment of the topic, "The Case for Space Solar Power" (published in 2014), which presented the first single-volume, integrated and detailed discussion of the topic in some 20 years.

In the past several years, new ideas for SSP in general and improvements in the SPS-ALPHA concept in particular have emerged. These include related developments in space and terrestrial technologies (e.g., reusable launch systems), new SSP activities internationally (e.g., new commercial efforts), as well as innovations in how SSP might be accomplished (e.g., in-space fabrication). This paper summarizes some recent studies of the SPS-ALPHA concept; it also reviews recent events in the SSP sector; and evaluates the potential impact of a new approach – SPS-ALPHA Mark-II – using new technologies and resulting concept evolution on the technical feasibility and economic viability of space solar power.

Part 1
INTRODUCTION

1.1 Background

Global demand for energy continues to expand with increasing populations and the need for improved economic conditions in all countries. Most of the world's energy is provided by fossil fuel combustion, and most of the projected future demand is expected to be as well. However, in December 2015, the great majority of Earth's nations, recognizing the urgent need to mitigate the looming risks of climate change, announced ambitious goals for the reduction of CO_2 emissions this century. In the judgment of many experts, these potentially-conflicting goals are unlikely to be accomplished solely through the use of already-existing technologies (such as hydroelectric power, terrestrial solar power (PV and CSP, and wind power). Among other important options, *space solar power* (SSP) remains one of the most-promising, but as yet largely undeveloped potential solutions to accomplish this goal.

1.2 The Need for New Energy Sources

There are three drivers of the urgent need for new energy sources: (1) growing global population; (2) improving per capita economic activity world-wide; and, (3) the need to mitigate climate change by reducing drastically emissions of carbon dioxide (CO_2) from electricity generation (and transportation). **Figure 1** summarizes the following generalized forecast.

Population Growth. In the early years of the 21st century (c. 2016), Earth's population surpassed **7.4** billion persons. By the year 2050, that figure is expected to exceed **9.7** billion, and by 2100 it is expected that some **11.2** billion people will inhabit this planet. Even with no change in the percentage of humanity living in poverty from 2016 levels, these additional billions will require vast new sources of electrical power.

Economic Progress / Electricity Use. Current (2016) total use of electricity is (very roughly) some 25 Billion MWh/year; however, this is changing, and quickly. During the same decades when Earth's population is projected to increase dramatically (see above), the *per capita* economic activity for those billions of individuals is also projected to increase - as will the demand for / use of energy in general, and electricity in particular. Overall, if by 2100 the *per capita* standard of living world-wide were to reach the level of energy use typical in Japan or Europe (in 2016) – which is about 50% of the use in the US – then the total power generation capacity globally must increase by 400%. This works out to about 50 Billion MW-hrs per year by 2050, and roughly 100 Billion MW-hrs by 2100. Where will that energy come from?

CO_2 Emissions and Climate Change. In looking back over the 20th century, economic activity has historically been linked tightly to emissions of CO_2 into Earth's atmosphere (largely from combustion of coal and oil). If there is no substantial change in the sources of energy, the above forecast of growth would result in an increase in annual CO_2 emissions from ~30 Billion MT in 2016 to ~60 Billion MT by 2050 and to ~120 Billion MT by 2100. These rates would result in increasing atmospheric CO_2 concentrations from 400 parts per million (2016) to 600 parts (2050) and to almost 1,000 parts per million (2100), and temperature increases compared to 2016 of 1°-2° Celsius in 2050, and as much as 3°-5° Celsius by 2100. All of the above would occur with much-discussed, potentially catastrophic impacts on Earth's climate and human communities.[1]

1.3 What is Space Solar Power?

Terrestrial ground-based solar energy will make an important contribution to the future energy mix. The same will be true for other options, including hydroelectric power and wind energy. However, each of these traditional renewable energy solutions has significant limitations – primarily intermittency (i.e., the energy is only available when the sun shines, when the wind blows, or the rains fill the reservoir behind a hydropower plant).

In a high Earth orbit, such as geostationary Earth orbit (GEO), the sunlight is available almost continuously (more than 99.8% of the time each year). The concept of harvesting solar energy in space and delivering it via wireless power transmission (WPT) is known as "space solar power" (SSP). The idea of SSP, first invented by Dr. Peter Glaser in the 1960s is one of the more promising ways in which the simultaneous challenges of energy growth and drastic CO2 emission reductions may be achieved.

However, past studies of SSP – beginning with early NASA-DOE efforts in the 1970s – resulted in solar power satellite (SPS) concepts that were extremely expensive to undertake.[2] For

[1] These issues are discussed in greater detail in "*The Case for Space Solar Power*" (2014).

[2] NASA: National Aeronautics and Space Administration; DOE: Department of Energy.

example, the so-called "1979 SPS Reference System" was estimated to require an investment of about $1,000,000,000,000 ($, 2016) to deliver the first kilowatt-hour (kWh) of electricity to a market on Earth. Fortunately, there have been numerous dramatic advances in technology since then – including photovoltaics, robotics, solid state electronics, materials, launch and many, many other areas.

For example, in 2000 a review of NASA's roadmap for SSP found that it was feasible, and that the development of space solar power would have tremendous value for future space programs. (This remains true today.) Then, during 2008-2011, the International Academy of Astronautics (IAA) conducted the *First International Assessment of Space Solar Power* (2011), involving diverse subject matter experts from some ten (10) countries. The IAA assessment found that using a modular approach SSP is technically feasible and that it might be realized in as little as 10-15 years.

Following on those results, in 2011-2012 an international team, working under the auspices of NASA's Innovative Advanced Concepts (NIAC) program examined a novel, more practical hyper-modular approach to realizing SSP: "SPS-ALPHA" (Solar Power Satellite by means of Arbitrarily Large Phased Array), invented by the author. Together, the IAA and NIAC studies provided the foundation of an integrated treatment of the topic, "*The Case for Space Solar Power*" (2014); this book presented the first single-volume, integrated and detailed discussion of the topic in some 20 years.

1.4 This Paper

Recently new ideas for SSP in general and improvements in the SPS-ALPHA concept in particular have emerged. These advances include related developments in space and terrestrial technologies (e.g., reusable launch systems), new SSP activities internationally (e.g., new commercial efforts), as well as innovations in how SSP might be accomplished (e.g., in-space fabrication). This paper will review recent events in the SSP sector, focusing on an evaluation of the potential impact of a new SSP concept: SPS-ALPHA Mark-II; it also discusses the economic viability of space solar using this approach, and concludes with suggestions for future work.

Part 2
CONCEPT OVERVIEW: "SPS-ALPHA" - Updated

When the SPS-ALPHA concept was created, there were a number of key issues that remained to be resolved. In the initial concept, very conservative materials were assumed (i.e., aluminum for primary structures) along with significant structural redundancy – as a result, masses were too high. Also, there were a number of unresolved key design details (such as detailed ray tracing for platform optics).

Because of these factors, the costs of electricity for the first SPS-ALPHA platform were greater than 15¢ per kilowatt-hour and required special government incentives to achieve economic viability. These issues and others drove efforts to improve the initial concept; the result is "SPS-ALPHA Mark-II". A relevant question: what are critical characteristics of the updated SPS concept? What are the differences between the initial SPS-ALPHA and the "Mark-II" version, presented here? The following is a brief summary of the revised SPS-ALPHA concept (2016).

2.1 Architecture Overview

The new version follows the same basic architecture, with various *Modules* integrated into *Assemblies*, which in turn comprise *Major Systems* within the overall architecture. See **Figure 2** for a high-level diagram of this approach. The following paragraphs present the major elements of the updated concept. **Figure 3** provides a visualization of the SPS-ALPHA Mark-II platform; it comprises many of the same elements as the original, with key differences; some are self-evident, while others are not.

Starting "at the top", so to speak, sunlight first intercepts numerous thin-film reflectors (each an individually pointed "heliostat") organized on an extremely large, tiered / conical structural frame. Together, the reflecting heliostats and the frame that supports them comprise the "Solar Reflector Array" (SRA). These very low-mass mirrors redirect incoming sunlight either directly to PV cells that cover the upper-side of the base of the platform, or to another mirror in the SRA and thence to the photovoltaics. This is the top surface of the "Power Conversion Array" (PCA). On the opposite, Earth-facing side of the PCA WPT transmitters are connected by local power management and distribution (PMAD) to the PV modules. Connecting the PCA and the SRA is a "Platform Structural Backbone" (PSB). These three elements comprise the majority of the updated SPS-ALPHA concept. [3]

The WPT panels of the PCA emit a coherent microwave transmission from GEO to a Terrestrial Receiving System (TRS), which includes a "rectenna" (i.e., a rectifying antenna), as well as other elements.

2.2 SPS-ALPHA Primary Features

The following is a more detailed summary of the primary features of the updated version of the SPS-ALPHA concept:[4]

- Significant updates to the SPS platform concept, including
  - Use of a truly hyper-modular architecture, with more than 1,000,000 small modules to create a single enormous solar power satellite platform through GEO-based assembly – reducing the size of the average module significantly
  - Addition of further details in the platform concept – involving the elaboration of the design to incorporate an additional 8-10 types of modular systems
- A significantly revised end-to-end WPT system, including
  - Continued use of microwave wireless power transmission (WPT) involving a retro-directive phase control signal with a secure pilot signal from Earth at the planned receiver – with a baseline assumption of 2.45 GHz (pending assignment of a specific WPT frequency between 1 GHz and 10 GHz)
  - Oversizing of the transmitter array / platform diameter (up to about 1,700 meters in the new baseline concept, as opposed to 1,000 meters in the earlier version) such that the size of the receiving Rectenna is no more than 6 km with a frequency of 2.45 GHz (about 3.5 miles)
  - Incorporation of a properly sized energy storage system with the receiver system so that it be fully independent of fossil fuel power supplies during eclipses at beginning of the spring (around March 20) and fall (around September 20), and on occasions when the WPT transmission must be briefly suspended due to spacecraft or aircraft transits, or for other reasons
- A revised transportation architecture, including
  - The option to use an expendable launch system (at sufficient scale and flight rate) in initial SPS deployment cases
  - Use of a single set of solar electric propulsion (SEP) propulsion modules to provide both LEO-to-GEO transport and in GEO north-south station keeping (NSSK) and attitude control (beyond that provided by the solar reflectors), eliminating the need for a separate fleet of reusable orbital transfer vehicles (R-OTVs)
- Changing the architecture of the platform to incorporate a single Solar Reflector Array

3 A detailed discussion of PV versus solar dynamic power conversion is outside of the scope of this paper; however, in brief: the high efficiencies now achievable with PV and entirely local thermal management, coupled with the operational simplicity of no moving parts and low voltage power management make PV the preferred solution.

4 See Figure 3 for a visualization of the updated SPS-ALPHA concept.

(SRA), eliminating the requirement for a secondary reflector array to be used in a Cassegrain Configuration, involving
  - o A simple "stepped cylinder" configuration – involving roughly only some four types of modules, with a single size of modular reflector.
  - o Set at an angle based on a simple, seasonally-varied ray-tracing analysis for daily continuous illumination of the PV array at all times of the year
- A potential reduction of 80% or more in annual operations and maintenance costs (also enabling extension of the expected life of the platform to more than 100 years) via
  - o Oversizing of the number of reflectors to enable use of the pressure of sunlight to provide two-thirds of required annual station-keeping delta-velocity
  - o Incorporating out-year deployment of additive de-construction and manufacturing systems onboard the SPS-ALPHA Mark-II to enable up to 90% "recycling" annually of failed platform hardware
- Revised SPS platform sizing, including
  - o Sizing the length of the backbone of the SPS platform and the individual PRA heliostats such that the reflected "image" of the sun (distorted by wrinkles, edges, etc.) for each reflector is no more than 3% of the light concentrated on any given square meter of the PV array – enabling the overall reflected sunlight to be uniform across the array
  - o Sizing the platform such that the concentration ratio used results in a temperature for the PV and solid state WPT electronics is no more than 100 °C (for the technologies involved in the baseline case, a concentration ratio of about 3:1)
- An updated concept of operations (CONOPS) that continues to baseline no human involvement in 'nominal assembly", with
  - o Use of more than 10,000 simple robotic arms (organized into more than 2,000 "hex-bot" assemblies) to enable the rapid assembly of the SPS platform (less than one year) – and then to use the same robotic arms to provide pointing and control of the numerous individual identical thin-film reflectors in the PRA
  - o Addition of the concept of a "Platform Kernel" to be launched first to GEO, and to provide the base of operations for SPS platform assembly and operations
  - o Using the modest "artificial gravity" created by the rotation of the long backbone of the SPS platform once every 24 hours to provide a convenient base for the concept of operations on the Earth-facing side of the "top" of the "structural backbone"

Additional details concerning the modules and critical technologies are discussed below.

2.3 Platform

The new version of SPS-ALPHA involves an updated and more comprehensive suite of "module species" – i.e., the various types of modular systems that together make up the platform. See **Figure 4** for a complete listing; it includes some sixteen (16) different modules, a significant increase over the eight modules that made up the original concept. In addition, a number of additional elements have been added comprising systems relating to supporting infrastructure (including, but not limited to the ground receiver mentioned above). The modules of the platform integrate to form some six (6) "Assemblies", that comprise the architecture's "Major Systems" (as described earlier); see **Figure 5**.

If the reader is familiar with the original version of the SPS-ALPHA, it will be clear that a primary module type is missing: the "HexBus" module. This module has been deconstructed into a redesigned version of the "Interconnect" module working in combination with a much simplified "Bus" module. See **Figure 6** for illustrations of several modules for the SPS-ALPHA Mark-II.

2.4 Transportation

There are three distinct aspects of transportation for all solar power satellites: (1) Earth-to-orbit (ETO) transportation, typically to low Earth orbit (LEO); (2) in-space transportation, to move SPS elements from LEO to the operational orbit, typically GEO, or a similar orbit; and, (3) platform station-keeping. In the baseline architecture for SPS-ALPHA Mark-II, it is assumed that ETO is provided by a reusable launch vehicle (RLV) – or partially reusable vehicle – capable of launch at costs of approximately $600 per kilogram to LEO.

Also, that in-space transport and a portion of required station keeping are provided by the same set of solar electric propulsion (SEP) in-space transportation systems – operating first as OTVs (orbital transfer vehicles) and then as station-keeping propulsion systems. (An evolution of this design is discussed below.)

2.5 Ground Systems

The primary ground system for any SPS architecture is a large receiver; in the case of a microwave wireless power transmission (WPT) system like SPS-ALPHA, this is a large diameter "rectifying antenna" (i.e., a "Rectenna"). In the standard reference case, usually involving a 1,000-meter diameter WPT transmitter, basing in geostationary Earth orbit, and the use of a 2.45 GHz frequency for transmission, the diameter of the Rectenna required for high efficiency may be calculated as approximately 10 km (at the equator); this was true for the 2014 SPS-ALPHA.

However, in the case of the updated concept, the transmitter is now projected to have a diameter of 1,700 meters – resulting in a diameter for the Rectenna of only 6,000 m (somewhat less than 4 miles), with an area of about 28 square kilometers (about 11 square miles). The power delivered is estimated to be approximately 2 GW.

In addition to various supporting ground infrastructure systems involving mission operations, the updated version of SPS-ALPHA also incorporates a significant change in the terrestrial receiver system: the addition of energy storage systems. Why are energy storage systems needed? There are three reasons: (1) scheduled outages due to shadowing of the SPS platform (occurring for varying lengths of time in mid-March and mid-September); (2) expected, but unscheduled outages due to spacecraft or aircraft passing over the receiver; and (3) unexpected and unscheduled system failures.

The baseline system must provide a maximum of 70 minutes of "full power", twice per year – in March and in September – and a lesser and lesser amount of stored energy for several weeks before and after the equinoxes. A central issue for this revision of the SPS-ALPHA concept lies in the cost per kW-hr of the energy storage systems, which will be driven by the installed cost per of the system, and its cycle-life. The economic analysis results presented below assume commercially viable and available energy storage systems.

2.6 Concept of Operations

The concept of operations (CONOPS) for the revised SPS-ALPHA platform is the essential aspect of activities following launch and transportation to GEO, comprising assembly, operations, maintenance and eventual repair and recycling. The has four primary tenets:

(1) autonomous robotic transportation, assembly and maintenance (modular robotics with no significant pre-planned astronaut participation; however, astronauts / humans on Earth would be involved in supervision, as needed during early SPS assembly);

(2) use of the modular systems used in deployment for other platform functions (including reflector pointing, station-keeping, etc.) during operations;

(3) reliance on a hierarchy of emergent behaviors for operations, communications, fault-detection, security, etc.; and,

(4) the introduction of a platform "Kernel" as the base where assembly begins (and which provides critical functions until these may be assumed by the growing SPS).

The details of the CONOPS will be the topic of a future paper; in the meantime, additional details are discussed below.

Part 3
SPS-ALPHA Mark-II ANALYTICAL RESULTS

The following section summarizes the results of recent systems analysis studies. These have been based on a set of technical key performance parameters (KPPs) that have been estimated for the SPS-ALPHA Mark-II. **Figure 7** presents at a conceptual level the inter-relationships among the diverse KPPs that characterize the SPS-ALPHA Mark-II system.[5] The KPPs that have been modeled in analyzing the updated SPS-ALPHA concept (which are not independent) include:

- Solar Flux Intercepted
- Platform Metrics
  - Hardware Mass
  - Hardware Manufactured Cost
  - Hardware Installed Cost
- WPT Sizing
  - Transmitter Diameter
  - Receiver Diameter
  - Transmission Frequency
- Power Generated / Delivered
- Temperature (PV & Electronics on the PCA)
- Annual Operations & Maintenance
- Platform Lifetime (and recycling)

The section that follows presents additional details concerning the analytical methods used to develop these results, and a number of systems analysis studies that have been performed to determine the sensitivity of these results to various assumptions regarding technologies and supporting infrastructure characteristics.

3.1 Analytical Methodology

There are a wide variety of physics-based factors and design considerations that must be incorporated into any analysis of an SPS concept. In developing an update of the SPS-ALPHA concept, entirely new spreadsheet based analytical tools were developed; an overview of this systems analysis model is presented in **Figure 8**. The tool includes the following primary elements: (1) a "controls" worksheet (where key parameters are set – such as the wavelength used for power transmission, the size of the transmitter array, etc.); (2) a technology database (which informs various specific module characteristics); (3) an "integration" worksheet; (4) a geometry and physics-based sizing worksheet, driven by KPPs specified on either the "controls" sheet or the "technology" sheet; and, (5) development of cost estimates, as described below.

Cost Estimation. Obviously, the central issue for evaluating any SSP concept is to be able to carefully estimate the costs of the architecture and the electricity provided. In the case of the methodology used here, that has been accomplished by (1) physics based sizing of the platform to deliver a certain amount of power; (2) estimation based on scaling laws of the number of modules of each type required to achieve a given platform; (3) estimation of the mass of each type of module based on a detailed subsystem breakdown and technology assumptions; (4) estimation of the development cost per kilogram for each module (based on specific cost estimation relationships (CERs); and (5) scaling of the CERs based on an assumed *Learning Curve* (LC) with a lower limit

[5] During the past several years, Mankins Space Technology, Inc. has continued to conduct a variety of analytical studies focusing on various considerations involving SSP in general and the SPS-ALPHA concept in particular.

such that costs cannot fall below approximately $100 per kilogram.

For the results presented here, the baseline case assumed a LC of 67%. **Figure 9** illustrates the sensitivity of the achieved LCOE to the assumed *Learning Curve* used. As shown, so long as the LC is less than 80%, LCOE from an initial platform of less than 10¢ per kW-hr can be achieved; even for this high value, the LCOE for multiple deployed SPS would fall to much lower costs.

The following sections present a variety of specific calculations and systems analysis results.

3.2 Structure and Reflector Sizing

Various design parameters are interrelated – and involve both natural constants and considerations of fundamental physics. For example, there are several factors that must be taken into account in order to properly "size" both the primary structures of the SPS-ALPHA, as well as the many reflectors required for the "Solar Reflector Array" within the system architecture. Note that there has been a significant change in the configuration of the SRA, from the earlier version of the concept.

Ray Tracing. Updating the reflector configuration for the SPS-ALPHA required a preliminary ray tracing analysis – including examination of the relationship between the size of an individual reflector, the size of the "spot" produced by that reflector at a given distance, and the expected "irregularity" in the surface of each reflector – resulting in an expected maximum "hot spot" on the PV cells. An important consideration of any concentrating solar power system (on Earth or in space) concerns whether or not the redirected and concentrated sunlight is sufficiently intense and irregular so as to create what are known as "hot-spots" on the solar receiver – whether it is a thermal system or a PV array. **Figure 10** illustrates at a very high level a portion of the ray tracing analysis that resulted in the updated configuration. (More detailed studies have been performed that confirm the overall approach.)

3.3 End-to-End Energy Analysis

An end-to-end analysis of the energy balance for the SPS-ALPHA is, of course, critical to understanding the system concept and to optimizing its design. Factors that were incorporated include: (1) energy input from the sun; (2) efficiency of the reflectors (and waste heat rejection); (3) PV array conversion efficiency and radiation of waste heat to space; (4) efficiency of power management and distribution; (5) conversion efficiency in the wireless power transmission (WPT) system; and, (6) rejection of waste heat to space from the WPT system. **Figure 11** presents a conceptual high-level diagram of the end-to-end energy "food chain".

Naturally, the assumed efficiencies of various steps directly impact the operating temperature of the various elements – and the total power delivered. **Figure 12** illustrates the sensitivity of the levelized cost of electricity (LCOE) delivered to variations in the efficiency of the WPT modules used. As shown, for the updated SPS-ALPHA, as long as WPT DC-to-RF conversion efficiency is greater than 50% the resulting LCOE will be less than 4¢ per kW-hr; and, if WPT efficiencies greater than 60% can be achieved, then the LCOE may fall below 3¢ per kW-hr. A closely related analysis of the sensitivity of LCOE to the allowable electronics operating temperature is presented in **Figure 13**.

3.4 Transportation

Affordable transportation to GEO remains a major challenge. However, the updated version of SPS-ALPHA described is far less sensitive to radical reductions in transportation costs than past SSP concepts. There are two major elements.

ETO Transport. As a result of the significant reduction in the average module size, mass and cost as compared to earlier SPS concepts (including the initial SPS-ALPHA), the updated concept is much less dependent on "very low cost" ETO transportation. **Figure 14** illustrates the relationship between the LCOE delivered and the cost of ETO transport.

As illustrated, for the baseline KPPs, the LCOE delivered does not rise above 10¢ per kilowatt-hour until the cost of ETO transport rises above $5,000 per kilogram. This is a tremendous result. It leads to the conclusion that launchers already in operation (e.g., the Falcon 9 of *SpaceX* – at $2,720 per kg), could be used now to begin SPS deployment. And, with vehicles already in development SPS-ALPHA LCOEs could be reduced below 5¢ per kW-hr. These vehicles include the expendable Falcon Heavy – at $1,650 per kg to LEO (as of August 2016) – or the partially reusable Falcon 9 of *SpaceX*, a LEO version of the reusable booster of *Blue Origin*, the fully reusable SKYLON concept of *Reaction Engines Ltd*., or others). To realize costs below 3¢ per kilowatt-hour for the baseline case, ETO transport at less than $800-$1,000 will be needed – a far cry from the $200 per kilogram that is frequently cited.

In the longer term, in order to reach electricity costs below 1¢ per kWh, the introduction of novel ETO systems (such as the all-electromagnetic *StarTram*) or the use of extraterrestrial materials (e.g., from the Moon or asteroids) may be needed. However, at this time it appears that with the revised SPS-ALPHA architecture, with launch below $1,000 per kg and recycling of platform materials, these options are attractive, but by no means crucial.

In-Space Transport. In past SSP concepts, it has typically been assumed that either (a) a stand-alone fleet of reusable orbital transfer vehicles (R-OTVs) will be needed to move pieces of an SPS from LEO to GEO; or, (b) the SPS would be assembled in LEO and then move itself to GEO. Neither of these is especially attractive (although the former was assumed in the initial version of SPS-ALPHA).

R-OTV "fleet" type approaches are challenged because high use of the vehicles involved (i.e., high energy density and fast trips times) results in poor fuel efficiency, whereas high fuel efficiency (i.e., low thrust electric propulsion) results in low use of the systems involved. In the updated concept (as mentioned above), it is assumed that the solar electric propulsion (SEP) and attitude control (SEPAC) assemblies that will be used to provide a portion of required station-keeping for the SPS will first be deployed in LEO and used to transport (one-way only) the operational packages of SPS pieces to GEO. This concept mirrors LEO-assembly self-transport concepts that were presented in the past.

By deploying SPS-ALPHA station-keeping modules in LEO and using them initially for in-space transportation, the need for a stand-alone in-space R-OTV is entirely eliminated – dropping costs considerably. As a result, the unique cost of LEO-to-GEO transport can be reduced to approximately the cost of the propellant used – which in turn becomes approximately the cost per kg of the ETO transportation system. This is an improvement on past concepts – particularly since it does not require the full deployment of the SPS platform in the orbital debris clouded environment of LEO. For purposes of the baseline SPS-ALPHA Mark-II concept, it is assumed that LEO-GEO transport is provided by a SEP system with a specific impulse (Isp – i.e., fuel efficiency) of some 2,500 seconds.

Assuming that a given LEO-to-GEO transport package would comprise a payload of about 100 MT (this could be aggregated in LEO from two or more ETO launches), then a 10,000 MT SPS would require 100 SEP OTVs for in-space transportation.

Platform Station-Keeping. As mentioned above, the SPS-ALPHA Mark-II concept proposes to use the LEO-GEO SEPS OTV as the propulsion modules for SSP platform station-keeping. In this way, the unique cost of station-keeping is reduced to the cost of propellant only to provide approximately 50 meters/second of delta-velocity per year for platform North-South Station Keeping (NSSK). For a platform of about 10,000 MT mass, and thrusters with an Isp of 2,500-3,500 seconds, this is equivalent to an annual propellant requirement of approximately 500-600 MT (or about 5-6% of platform mass per year).

Can this requirement be eliminated and/or mitigated significantly? The answer appears to be yes.

Photon Pressure and Station-Keeping. Of course, the prevailing photon pressure at one (1) astronomical unit (AU) from our Sun is quite tiny. However, given the use of large-area thin-film solar sails to accomplish the redirection of incoming solar energy, two questions present themselves: what will be the resulting photon pressure? and how best to use that pressure?

Solar photon pressure at 1 AU, for a reflector with a total reflectivity of some 80% can be calculated as a maximum of some 0.000008208 Newtons (kg-m/s^2) per square meter of reflector – i.e., about 0.01 milli-Newtons per square meter of reflector. This compares with values on the order of 100-300 milli-Newtons produced by Hall Effect electric thrusters of the type that are assumed for the SPS-ALPHA Mark-II concept.

As a result, one can guesstimate that some 10,000 to 30,000 square meters of solar sail would be needed to produce thrust equivalent to one SEP thruster at 1 AU. And, for a 10,000 MT SPS (requiring annual NSSK as above) a constant force of some 31.7 N would be needed. This leads to a total reflector area of perhaps 3,860,000 m^2 (a circle with a radius of 1100 m).

As described elsewhere, the updated SPS-ALPHA concept involves a total of some 10,000 reflectors, with about 50% being used on average for power generation at any given time. A typical reflector in the concept would be perhaps 30 meters in diameter, with an area of about 500 or more square meters. If this rough initial analysis is verified, then roughly 100 heliostats would be required to replace each Hall Thruster. The above line of thought suggests that replacing some 100 SEP propulsion modules would require only an additional 10,000 reflectors, or substantially fewer if the diameter of the reflectors is allowed to increase.

Since the total mass of the Solar Reflector Array (SRA) is about 400-500 MT (about 4%-5% of the total); this implies that only a very modest increase in the total mass of the SPS-ALPHA Mark-II (about 10,000 MT) This is a very interesting result; it suggests that one of the major sources of annual O&M transportation to an SPS in GEO might very well be replaced by oversizing the SPS platform's reflector array.

Clearly this is an extremely useful area for additional analysis in future to confirm that this initial analysis holds up under more detailed scrutiny.

3.5 CONOPS & Platform Assembly

A central issue in the evaluation of the alternative SSP architectures is the question of how platform assembly would actually proceed. This topic was addressed at a high level in Chapter 8 of *The Case for Space Solar Power*, which discusses the "concept of operations" (CONOPS) for SPS-ALPHA. There are three significant approaches incorporated in the CONOPS for the Mark-II concept: (1) use of a "Kernel" as a base for assembly; (2) exploiting the artificial gravity generated by the long backbone structure; and, (3) the role of recycling of failed platform modules through the use of in-space manufacturing to make the SPS platform essentially permanently operational.

CONOPS and the "Kernel". As sketched in *The Case for Space Solar Power*, the concept for SPS-ALPHA assembly and operations assumes that an initial spacecraft than other modular elements is first deployed to the orbital "site" at which the platform will be constructed. This is the "Kernel" of the platform. This approach was used with great success in the deployment of the International Space Station (ISS).[6] In the case of SPS-ALPHA, the "Kernel" would be launched first, and would provide a fixed infrastructure

6 The first ISS module, provided by Russia was called "*Zarya*" and was also known as the "Functional Cargo Block" (FGB). The FGB provided electrical power generation and storage, propulsion, guidance, etc.to the *ISS* during the *initial* stage of assembly.

for rendezvous and docking of subsequent cargo deliveries, communications, attitude control, propulsion, power, etc.

CONOPS and "Spin". How and where to manage the numerous pieces of an SPS is quite important – including arrival of new modules, but also storage of those that have been damaged– particularly during assembly, but also during the life of the platform (e.g., during the arrival of spare parts, etc.). A very interesting result of the recent studies has been the finding that the long backbone structure required to avoid "hot spots" – discussed elsewhere – results in a small but meaningful artificial gravity effect on the GEO-based platform (which rotates once each 24 hours). As a result, a preferred location for various platform assembly operations emerges: in the immediately proximity of the Kernel (described above) on the underside of the docking location at the far-end (away from Earth) of the platform.

CONOPS and Recycling. A central consideration in determining the "levelized cost of electricity" (LCOE) produced by any power source is that of the lifetime of the physical plant and equipment involved. Power plant lifetimes are typically projected to have at perhaps 20-40 years. In some cases, longer operating lives are projected, including nuclear power plants (e.g., c. 50 years) and hydroelectric power plants (e.g., c. 100 years).

There are two approaches by which to achieve very long lived SSP systems: a long life for the initial power plant (piece parts and total system) and/or recycling of the piece parts of the initial SPS. During examination of the characteristics of the initial SPS-ALPHA, it became evident that there is no possible way that governments or commercial firms would deploy a 10,000 MT platform in GEO and then throw the platform away after only 30 or so years or use. Recycling of the modular elements of the platform is only sensible – and with the emergence of additive manufacturing in space, it is entirely possible.

A more detailed examination of the concept of recycling is needed, of course. However, recent advances in in-space additive manufacturing suggests that within 10-15 years the concept should be entirely viable from a technical standpoint.

Figure 15 illustrates the sensitivity of the delivered LCOE to lifetime of the SPS platform; as shown, so long as the operational lifetime of the platform is greater than 20 years, the LCOE for the electricity delivered will be below 4¢ per kW-hour. If – for example, with recycling – the life of the platform can be extended beyond 50 years, the LCOE fall below 2¢ per kW-hr.

3.6 Energy Storage

Earlier version of SPS receiver systems (including those for SPS-ALPHA) did not generally include any accounting for possible energy storage systems at the receiver. The updated SPS-ALPHA Mark-II concept does include energy storage – a significant additional cost for the total installed infrastructure. However, there are clear requirements for that capability – especially if SSP is to deliver a substantial fraction of humanity's total generation capacity locally or globally. First and foremost, there will be short-duration outages during shadowing of the SPS in GEO by Earth during the several days before and after the Spring and Fall "equinox". These periods will occur around local midnight, but would last for a bit more than one hour on the day of the equinox.

In order to mitigate these outages, there are three basic approaches: (1) an alternate source of power for customers (e.g., natural gas turbines), (2) energy storage onboard the SPS platform, or (3) energy storage on the ground. Of these options – and given recent advances in energy storage technologies – ground-based energy storage provides the lowest-cost, self-sufficient solution to satisfy this need. What are the requirements involved?

The maximum duration of shadowing (at March 21, and at September 21) is roughly 70 minutes, where the shadowing begins about two weeks earlier, with a duration of moments increasing to the maximum; and, the total duration of shadowing each year is approximately 3 hours (180 minutes), including the full time before and after each of the two equinoxes. This energy storage could be provided by a combination of local storage at the receiver and regional storage associated with local grid systems.

In the case of GEO-based communications satellites – for which data is the product delivered – these eclipses demand that energy storage be provided on-board the spacecraft. However, in the case of SPS, where power is delivered, this is unnecessary.

The preceding discussion has summarized the results of diverse recent analyses of the SPS-ALPHA (Mark-II) concept, and various updates of the design.

Part 4
ECONOMICS

There are three primary questions vis-à-vis SPS-ALPHA economics: (1) would space solar power from SPS-ALPHA contribute to accomplishing international climate change goals? (2) can this service compete in energy markets? and, (3) is there an economically viable path to large scale deployment of SPS-ALPHA space solar? The first question is easy to answer.

4.1 Near Zero Carbon Energy

If it is low carbon emitting, then solar energy harvested in space would be included in government incentive programs focused on climate change objectives. And, such inclusion could significantly enhance the early economic performance of SSP. Fortunately, the energy required for SPS-ALPHA manufacture and deployment should be quite tractable. For example, in the case of a conventional ground solar power system, about 1,000 kWh is required to manufacture each square meter of a PV array. With typically efficiencies of 10%-15%, in an average location in the US, this translates into about 18 months for "energy payback", with total energy produced of approximately 1,700 kWh per m^2 per year. With a lifetime of about 30 years, such PV arrays produce dramatic net carbon reductions for the climate.

In the case of SPS-ALPHA, there are two major components to the energy investment: manufacturing the platform, and deploying it to GEO. The deployment energy cost is easy to estimate: a total change of energy of 15,000 meters per second is required for transport from Earth to GEO, which works out to about 32 kWh per kilogram deployed. Since the total mass of the platform is about 10,000,000 kg for a net power delivered of about 2,000,000 kW (about 5 kg/kW), daily energy is 48,000,000 kWh, or some 4.8 kWh/kg/day. As a result, the time to payback the transportation energy cost is only about 6 1/2 days. That is a tremendous result: the energy cost of deployment to space is trivial. [7]

What about the energy required to manufacture the SPS? A detailed "energy cost" analysis is needed, of course; however, a rough estimate can be made quickly. First, we must assume that the energy cost per square meter of the SPS PV arrays is approximately the same as the energy cost per square meter for ground PV; recall from the section above, that this is about 1,000 kWh per m^2. Because the total mass of the solar power generation system on the SPS-ALPHA Mark-II is about 1,900 MT with a total PV area of 2,400,000 m^2, that translates into a specific energy cost for the SPS PV arrays of about 1262 kWh/kg. Second, if we also assume that the energy cost per kg for an average kilogram of SPS platform is roughly the same as that of the PV on the SPS, then since the energy produced by the whole SPS is 4.8 kWh/kg/day (see above), this results in an SPS energy payback time of 263 days – or just about 9 months. This compares well to the value of about 18 months for grid-tied, intermittent ground-based PV – i.e., without energy storage. In other words, if fossil fuel energy were used to fabricate and

[7] The energy payback times for various renewable and non-renewable energy sources present an interesting contrast; see the reference.

deploy either ground solar power systems (without energy storage) or an equivalent SPS-ALPHA, the latter requires only half as much CO_2 emissions as the former. If the ground solar power systems were deployed with energy storage and were to be oversized to allow for day-night cycles and overcast weather this comparison swings dramatically more in favor of SPS-ALPHA.

All in all, SPS-ALPHA appears to support climate change mitigation goals extremely well.

4.2 Can Space Solar Compete?

If the KPPs discussed in the previous section can be realized, the overall economics for SPS-ALPHA Mark-II may be quite remarkable. From the first full-scale solar power satellite, up to 2 GW of electricity can be delivered, with costs of electricity below 10¢ per kWh for ETO costs of less than $4,000 per kg, and below 3¢ per kWh for ETO less than $1,000 per kg.

Looking at global electricity demand (which includes markets such as Hawai'i, Japan and others with prices of 25¢ per kWh or more), the potential exists for significant net revenues, even during the first year. Moreover, payback times are potentially excellent. First, the transportation-related energy payback time is on the order of seven days. Although longer, the financial payback time in the higher-end markets could be on the order of 2-3 years, based on sales of 17.5 Million kWh per year at 25¢ / kWh, and an LCOE of 3¢ / kWh.

Figure 16 provides the summary results of an illustrative integrated economic performance evaluation of the Mark-II concept. Findings include payback times on the first SPS within less than two (2) years; and a total capacity of some 2 TW (a fraction of total demand, see above) in 2100 could be reached, resulting in delivery of more than 15 Billion MWh/year of electricity. Annual net revenues by 2100 are estimated at $900 Billion, while a total of 3 billion MT of projected CO_2 emissions might be avoided.[8] Given that the total global demand (described above) for electricity by the year 2100 is projected to reach perhaps 100 Billion MWh, this would represent a market share for SSP of approximately 15%. This is large, but not at all inconsistent with current major sources.

4.3 An Economically-Viable Path

The last question posed for SPS-ALPHA economics is that of whether there is an economically viable path forward for the development of this approach to space solar power. There are three questions: (1) how much would the first SPS-ALPHA cost? (2) how much would it cost to demonstrate the technologies and systems required? and, (3) are there economically useful (i.e., profitable) markets to which interim accomplishments (e.g., sub-scale demos) could be applied?

As discussed above, the cost of the first SPS-ALPHA (Mark-II) would be approximately $11B, for power delivered of some 2.1GW. This is a considerable investment, but quite consistent with other major power projects and power plants. For example, the 3 Gorges Dam Project in China cost between $40B-$80B (including recent renovation efforts), for available capacity of about 10 GW, average. A different type of infrastructure, Boston's "Big Dig" transportation project cost about $24B. In yet another quite different project, The Boeing Company's development of the 777 aircraft cost somewhat less than $10B. So, projects of comparable scale to the SPS-ALPHA are tractable for national governments, municipalities and companies – if the value justifies the investment.

A roadmap for the development of SPS-ALPHA, including the costs and timeframes for various stages of development and

[8] Where this project assumed that sources displace by space solar are average, fossil fuel sources.

demonstration is discussed at some length in *The Case for Space Solar Power* (2014). Although this needs to be updated to reflect the design improvements and cost reductions described for here for the updated version of the concept, the basic scenario is unchanged: development of SPS-ALPHA, involving several cycles of “design-build-test-repeat” would require no more than 1-2 years to ground demonstrations on the order of 10s of kW (Stage A), 4-6 years to a first demonstration in space, on the order of 50kW on board (Stage B), and 6-10 years to a first operational SPS prototype in GEO, on the order of multiple MW on board the platform in space (Stage C).

At present, the costs may be estimated as approximately: $10M (Stage A), $100M-$200M (Stage B), and $2B-$5B, depending on the power level achieved (Stage C). It must be noted that the emergence of commercially-available launch options has changed the costs for this roadmap significantly.

Finally, are there markets for the above interim steps that would be needed to realize SPS-ALPHA? At present, the cost of power in near-Earth space range from $25 to $100 per kilowatt-hour – as compared to costs of baseload electricity on Earth of from 5¢ per kWh to about 50¢, depending on the market and the sources of energy employed. As a result, there are a wide range of prospective markets for affordable and sustainable space solar power *in space*. Probably the most attractive of these is the communications satellite market.

In particular, the cost of a typical conventional GEO communications satellite (comsat) is about $100M with onboard power of some 10 kW delivered to the RF system (i.e., the microwave transmitter). That works out to about $10,000,000/kW-RF produced. For an early “sub-scale” SPS-ALPHA demonstration, a higher power level (e.g., 50 kW) could be delivered to an onboard RF system, and at much lower specific cost (e.g., estimated at some $200M total, or $4,000,000/kW-RF); this is less than 50% of the cost per unit power, and five-times the number of transponders (and revenues). Future GEO comsats built based on SPS-ALPHA architecture could achieve far lower costs as production of the modular elements matured. Given that the annual market for comsat services has been assessed at more than $120B per year, it seems likely that higher revenue satellites at much lower costs could do very well in this market.

Overall, the economics of SPS-ALPHA appear particularly attractive: the costs and schedule to develop the technology are both tractable, and can be offset with interim applications and markets, while the costs of an initial SPS platform are quite comparable to other large power, infrastructure and commercial projects – while the profitability of SSP could be quite good in diverse markets globally.

Part 5
RECENT PROGRAMMATIC ACTIVITIES

In addition to the studies and design updates discussed above, there have also been a number of important programmatic activities that must inform planning with regard to SSP. The following section discusses activities in the United Stations (US), activities in Japan, activities in China, and (briefly) activities in various other countries.

5.1 Activities in the US

There have been three interesting recent activities in the United States (US) related to space solar power. The first of these (at least in the eyes of the author) is the development of the SPS-ALPHA Mark-II concept – described in this paper. There have been two others: (1) the emergence of interest by the US government, and (2) an ongoing joint project involving the Northrop Grumman company and the California Institute of Technology (CalTech) in March 2016.

US Government. There have been a handful of interesting developments in the US Government. During late summer 2015, the Defense Advanced Research Projects Agency (DARPA) organized a small workshop on the topic of space solar power. In addition, beginning in the fall of 2015, the US Government undertook a significant inter-agency competition (the so-called "D3" competition, where "D3" referred to "development, defense and diplomacy") that attempted to find novel solutions to important problems facing the United States. This competition was jointly sponsored by the US Department of State (DoS), the US Department of Defense (DoD) and the US Agency for International Development (USAID). The result, after some six (6) months was the selection of the space solar power team (lead by Dr. Paul Jaffe of the US Naval Research Laboratory) as the winning project.

US Industry. There have been several developments at various levels within US industry vis-à-vis SSP and related technologies. One of the more exciting new activities concerning SSP involves an R&D partnership focused on space solar power (SSP) between the Northrop Grumman Corporation and CalTech. This collaboration, established in 2014 and a stated three-year term, is examining the potential for a "microwave swarm" approach to SSP.

Of course, there are continuing activities by several other players in the US. These include ongoing efforts by *Solaren* (a California company in the Los Angeles area), dedicated to the development of their unique SPS concept, as well as more recent efforts involving Northrop Grumman in partnership with the California Institute of Technology (CalTech), related to SSP technology R&D. In addition, a new start-up "Mankins Space Technology Inc." (the author of this paper is the founder) undertook significant independent research and analysis – resulting in the updated SPS-ALPHA concept described in this paper.

Non-Profits. The US National Space Society (NSS) continues to organize an annual track on SSP at the International Space Development Conference (ISDC). The ISDC has included for the past several years a visualization competition focused on advancing concepts for, and broad communications related to SSP; this competition has been supported by *SPACE Canada* (see below).

In another development in the US, the MacArthur Foundation – a non-profit institution – released a call for applications for a major new grant opportunity in early June 2016 (with a total value of $100,000,000 to a single winning application). The "100&Change" competition had as its stated goal the solution of some major global problem. Not surprisingly, a number of proposals concerning space solar power were submitted by various organizations.

5.2 Activities in Japan

In addition to ongoing academic and not-for profit SSP activities in Japan, there have also been significant efforts during the past several years by both government and industry players.

Government. Japan Space Systems (JSS), formerly the Unmanned Experiments Free Flyer Institute (USEF) with sponsorship from METI (Ministry of Economy, Trade and Industry), based in Tokyo has conducted SSP and WPT related R&D for many years, in cooperation with the Japan Aerospace Exploration Agency (JAXA). In 2014-2015, the national space policy of Japan changed, resulting in space solar power becoming a part of other policy goals, rather than being a goal in and of itself. Also, in spring 2015, two major demonstrations of microwave wireless power transmission (WPT) were completed. These tests, sponsored under the auspices of the METI, JAXA and industry. In October 2016, METI organized the 3rd Annual Innovation for a Cool Earth Forum (ICEF), at which SSP was discussed outside the space community as a candidate solution to the challenge of reducing CO2 emissions. (Other topics discussed included conventional renewable options, as well as nuclear fission reactors, and fusion reactors.)

Industry. The WPT tests mentioned above were accomplished by two parts of Mitsubishi: MELCO (Mitsubishi Electric Company) and MHI (Mitsubishi Heavy Industries). In addition to the microwave WPT demonstrations mentioned, a leading WPT researcher in Japan, Dr. Nobuyuki Kaya, Professor Emeritus of Kobe University, formed a new for-profit firm (Advanced Microwave Arrays, Inc.) that is actively developing technology for future microwave array systems, including in the longer-term WPT concepts.

5.3 Activities in China

There are a variety of activities related to space solar power R&D in China. The most significant of these (in terms of international visibility) are related to the efforts of CAST *vis-à-vis* SSP.

The China Academy of Science (CAS) has a continuing interest in SSP, emphasizing advanced materials research for SSP applications. The *China Academy of Space Technology* (CAST) has been undertaking SSP research and development for more than 10 years. Dr. Li, Ming (deputy director of CAST) has pursued the topic since the early 1990s. At the International Astronautical Congress (IAC 2016) held in Guadalajara, Mexico it was reported that the value of SSP related R&D in China for the current year was in excess of $5 Million.

Activities have been targeted on (among other topics) (1) a traditional SPS concept (with a main body hosting the WPT array, with two PV array “wings”), and issues such as assembly of such a platform and alternatives; and, (2) an alternative – the so-called “SPS-OMEGA” – that involves a spherical reflector array approach with a centralized, bod-mounted PVC array with a large fixed PMAD system.

5.4 Other International Activities

In addition to various national and corporate activities, there were also SSP related activities led by a number of different non-governmental organizations. These groups have included the International Astronautics Federation (IAF), SPACE Canada, and the National Space Society (NSS); their efforts are sketched below.

- The *International Astronautics Federation* (IAF) includes a “Power Committee” that has organized for more than 25 years an annual international symposium on the topic of space power – including 2-3 sessions on SSP (involving 6-10 papers in each). This has included for the past several years a student competition, focused on advancing concepts for and understanding of SSP. This student paper competition has been supported by *SPACE Canada*, discussed below.
- *France – Reunion Island* has (September 2016) reopened local government consideration of creating a wireless power transmission testbed, related to providing power to the geographically isolated community of *Grand Basin*. (This idea was discussed earlier – circa 2001.)
- *SPACE Canada* is a non-governmental organization (NGO) based near Toronto, Canada; the objective of the organization is to promote an international dialogue on the topic of space solar power. *SPACE Canada* played a leading role, along with the *International Academy of Astronautics* (IAA) on SSP, the “SPS 2009” conference at the Ontario Science Center located in Toronto, Canada.
- The *Korean Academy of Science and Technology* (KAST) has organized a discussion of SSP at the upcoming (November 2016) 2016 Inter-Academy Seoul Science Forum on “Earth, Space, Human and Future”.

Part 6
FUTURE DIRECTIONS

A great deal of progress has been made in advancing space solar power during the past couple of years. However, there is much work yet to accomplish. For example, there is a need for additional, detailed analysis of the updated SPS-ALPHA concept, including particularly the structural dynamics of the platform and mechanical interfaces and loads on the various modular elements. Also, there is a need for an updated Technology Readiness and Risk Assessment (TRRA), including evaluation of the Technology Readiness Levels (TRLs), Research and Development Degree of Difficulty ($R\&D^3$) and Technology Need Value (TNV) for the various technologies that are involved.

In addition, there is a need for an updated roadmap describing how one might proceed with the development of SSP on the SPS-ALPHA model. Given the extensive work that has been accomplished, this roadmap could now be much more detailed than was possible just two years ago. And, of course, there is an urgent need to begin focused technology maturation R&D and demonstrations that follow the path of that roadmap toward the realization of sustainable, affordable energy for humanity.

A number of these items will be discussed in the 2nd Edition of "The Case for Space Solar Power", planned for release in 2017.

Part 7
SUMMARY & CONCLUSIONS

There is an urgent need for new sustainable energy sources that can be scaled to deliver power globally. Tremendous advances have been achieved in making the two primary sustainable new energy sources of the past 40 years – wind and ground solar – economically viable. These sources are being deployed globally. However, these sources are inherently intermittent; neither provides the nearly continuous "base load" electricity needed to power industrial society.

Space solar power (SSP) represents a different approach, one that <u>can</u> deliver base load power in 100s to 1,000s of GW by mid-Century and later, to markets around the world. However, SSP has been considered since the late 1960s, and has not yet achieved the needed combination of technology readiness, program credibility and economic viability that might enable this new approach to go forward.

This paper has reviewed recent advances toward the vision of "space solar power" (SSP), focusing on an update of the promising hyper-modular concept of "SPS-ALPHA Mark-II" and various SSP-related programmatic developments. As presented above, the new version of SPS-ALPHA represents a dramatic improvement in the expected technical characteristics and resulting economics for SSP – with 2 GW of power delivered with electricity costs below 3¢ per kWh achievable with ETO costs below $1,000 per kg.

The baseline SPS-ALPHA concept is described in much greater detail in "*The Case for Space Solar Power*" (2014); additional details concerning "SPS-ALPHA Mk-II" will be presented in the second edition of this book (planned for release in 2018).

Special Note

In closing, the author wishes to make special note of the passing in 2015 of two giants: Dr. Peter Glaser (May), the inventor of the solar power satellite (SPS) in the 1960s and of Dr. Abdul Kalam (July), known affectionately as "the missile man" for his leadership in advancing space technology in India and as former President of his country. Dr. Kalam was a tireless advocate of a better future for the people of India and the world – including space solar power. The author was privileged to have met both of these visionaries – one from near Prague in the former Czechoslovakia (1923) and the other born in Rameswaram in India (1931). The world is a better place for their having lived and a lesser place now that they have passed.

Part 8
GLOSSARY OF ACRONYMS

AU Astronautical Unit (1 AU is defined as the average orbital distance of Earth from the Sun)

CalTech	California Institute of Technology
CAST	China Academy of Space Technology
Comsat	Communications Satellite
CONOPS	Concept of Operations
CSA	Canadian Space Agency
CSP	Concentrator Solar Power
D3	Defense, Diplomacy, and Development (Tech Innovation Challenge)
DARPA	Defense Advanced Research Projects Agency
DOD	(US) Department of Defense
DOE	(US) Department of Energy
DoS	(US) Department of State
ESA	European Space Agency
ETO	Earth to orbit
FGB	Functional Cargo Block (on the ISS; acronym is from the Russian)
GEO	Geostationary Earth Orbit
GW	Gigawatt
HRST	Highly Reusable Space Transportation (Vehicles)
JAXA	Japan Aerospace Exploration Agency
IAA	International Academy of Astronautics
IAC	International Astronautical Congress
IAF	International Astronautical Federation
ICEF	Innovation for a Cool Earth Forum
ISDC	International Space Development Conference
Isp	Specific Impulse
ISRO	Indian Space Research Organization
ISRU	*In Situ* Resource Utilization
ISTS	International Space Science and Technology Symposium (JAPAN)
KARI	Korean Aerospace Research Institute
KAST	Korean Academy of Science and Technology
kg	kilogram
km	kilometer
KPP	key performance parameter(s)
kW	kilowatts
kWh	kilowatt-hours (also "kW-hrs")
LCOE	Levelized Cost of Electricity
LEO	Low Earth Orbit
m	meter
METI	(Japan) Ministry of Economy, Trade and Industry
MW	megawatt
MWh	megawatt-hours
N	Newton (a unit of force, defined as one kg-meter/second-squared)
NASA	National Aeronautics and Space Administration
NIAC	NASA Innovative Advanced Concepts (Program)
NGO	Non-Governmental Organization
NREL	(US DOE) National Renewable Energy Laboratory
NRL	(US) Naval Research Laboratory
NSS	National Space Society
NSSK	North-South Station Keeping
OTV	Orbital Transfer Vehicle
PCA	Power Conversion Array
PCAS	Power Conversion Array System
PMAD	Power Management and Distribution
PSB	Platform Structural Backbone
PV	Photovoltaic
RAA	Reflector Array Assembly
RAS	Reflector Array System
R&D^3	Research and Development Degree of Difficulty
Rectenna	Rectifying Antenna
RLV	Reusable Launch Vehicle
R-OTV	Reusable OTV
SAMS	Space Assembly, Maintenance & Servicing
SEPAC	SEPS and Attitude Control

SEPS Solar Electric Propulsion System
SPG Solar Power Generation (Module)
SPS Solar Power Satellite
SPS-ALPHA SPS by means of Arbitrarily Large Phased Array
SRA Solar Reflector Array
SSP Space Solar Power
TNV Technology Need Value
TRRA Technology Readiness and Risk Assessment
TRL Technology Readiness Level
TRS Terrestrial Receiving System
TW Terawatt
USAID (US) Agency for International Development
WPT Wireless Power Transmission (Module)

Part 9
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Part 10

FIGURES

Figure 1 Forecast of the Need for New & Sustainable Energy Sources

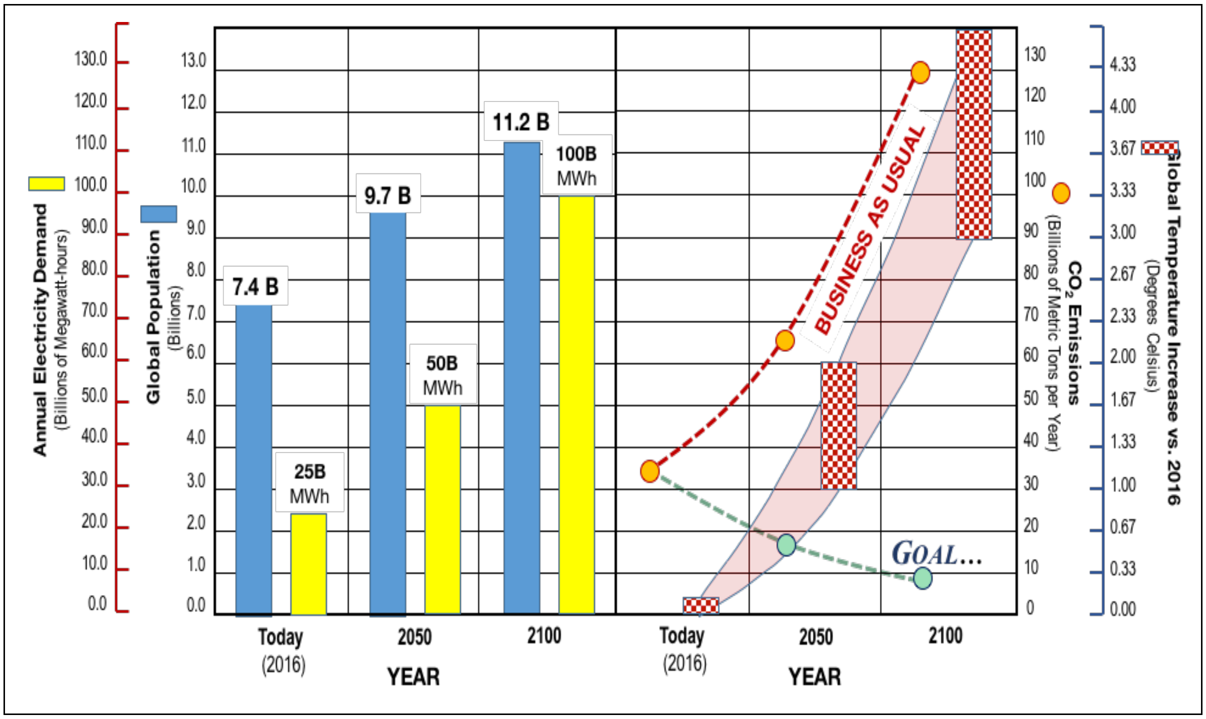
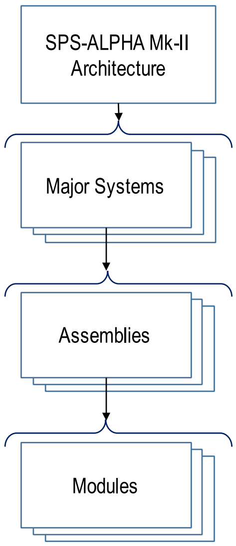


Figure 2 SPS-ALPHA Architecture Overview



- At the highest Level, the full Architecture, comprising the SPS Platform, Ground Systems, Supporting Infrastructure, etc.
- At the 2nd Level, the Major Systems within the Architecture
    - Within the Platform, comprising the Reflector Array, etc.
    - On the Ground, including the Rectenna, etc.
    - In the Transportation Infrastructure, including the Launch Vehicle, etc.
- At the 3rd Level, the Assemblies within each Major System
    - Including the Reflector Array Assemblies, comprising interconnects of two types, truss structures, reflector deployment modules, etc.
- At the 4th Level, the various modules that comprise the SPS-ALPHA Mark-II Architecture

Figure 3 SPS-ALPHA Architecture Visualization

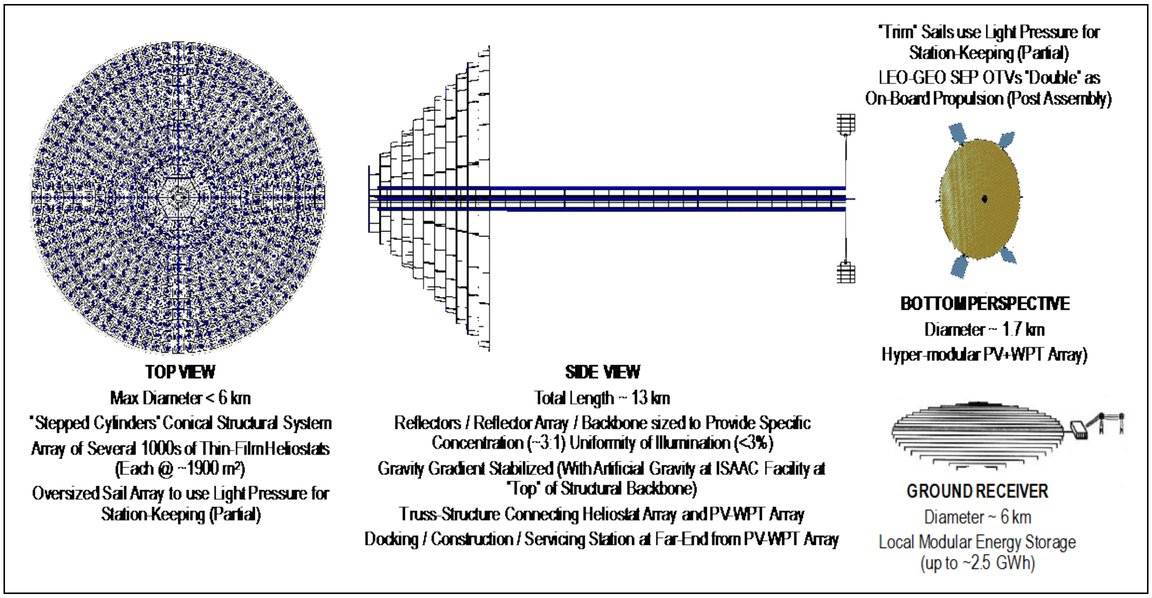


Figure 4 SPS-ALPHA Architecture Breakdown 1 of 2: Major Systems

1. SPS-ALPHA Mark-II Platform Systems (M.1)	2.0 Ground Receiver Systems (M.2)

• Inter-connect Modules (M.1.1)
  ◦ Inter-connect - Type 1 (M.1.1.1)
  ◦ Inter-connect - Type 2 (M.1.1.2)
• SPS Bus Module (M.1.2)
• SPS Frame Modules M.1.3)
  ◦ Frame - Type 1 (Long; M.1.3.1)
  ◦ Frame - Type 2 (Short; M.1.3.2)
• Wireless Power Transmitter Module (M.1.4)
• Solar Power Generation Module (M.1.5)
• Thin-Film Heliostat: Reflector & Deployer Module (M.1.6)
• Robotic Arm Manipulator System Module (M.1.7)
• Propulsion Module (M.1.8)
• WiFi Router Module (M.1.9)
• External Communications Module (M.1.10)
• Autonomous Rendezvous & Docking (AR&D) System Module (M.1.11)
• "Kernel" Core Module (M.1.12)
	• M.2.1 Rectenna Antenna (M.2.1)
	• Pilot Signal Transmitter (M.2.2)
	• Range Safety & Control (M.2.3)
	• Energy Storage Systems (M.2.4)
	• Grid Interfaces (M.2.5)
	3.0 Launch Systems (M.3)
	• Launch Vehicle (M.3.1)
	• Payload Support & Packaging (M.3.2)
	• Transportation Ground Infrastructure (M.3.3)
	• Transportation Mission Control & Communications (M.3.4)
	4.0 In-Space Transportation Systems (M.4)
	• Orbital Transfer Power Systems (M.4.1)
	• Orbital Transfer Thermal Systems (M.4.2)
	• Orbital Transfer Ground Infrastructure (M.4.3)
	5.0 SPS Mission Control Center (M.5)

Figure 5 SPS-ALPHA Architecture Breakdown 2 of 2: Assemblies → Modules

1.0 Power Conversion Array Assembly (A.1)

- Inter-connect Modules (M.1.1)
  - Inter-connect - Type 1 (M.1.1.1)
  - Inter-connect - Type 2 (M.1.1.2)
- SPS Bus Module (M.1.2)
- Wireless Power Transmitter Module (M.1.4)
- Solar Power Generation Module (M.1.5)
- WiFi Router Module (M.1.9)
- External Communications Module (M.1.10)

2.0 Primary Reflector Array Assembly (A.2)

- Inter-connect Modules (M.1.1)
  - Inter-connect - Type 1 (M.1.1.1)
  - Inter-connect - Type 2 (M.1.1.2)
- SPS Bus Module (M.1.2)
- SPS Frame Module M.1.3)
  - Frame - Type 1 (Long; M.1.3.1)
  - Frame - Type 2 (Short; M.1.3.2)
- Thin-Film Heliostat: Reflector & Deployer Module (M.1.6)

3.0 Platform Backbone Structure Assy (A.3)

- Inter-connect Modules (M.1.1)
  - Inter-connect - Type 1 (M.1.1.1)
  - Inter-connect - Type 2 (M.1.1.2)
- SPS Bus Module (M.1.2)
- SPS Frame Module M.1.3)
  - Frame - Type 1 (Long; M.1.3.1)
  - Frame - Type 2 (Short; M.1.3.2)

4.0 SPS Orbital Operations Assembly (A.4)

- Inter-connect Modules (M.1.1)
  - Inter-connect - Type 1 (M.1.1.1)
- SPS Bus Module (M.1.2)
- Solar Power Generation Module (M.1.5)
- Propulsion Module (M.1.8)
- WiFi Router Module (M.1.9)
- External Communications Module (M.1.10)
- Autonomous Rendezvous & Docking (AR&D) System Module (M.1.11)

5.0 SPS On-Board Operations Assy (5.6)

- Inter-connect Modules (M.1.1)
  - Inter-connect - Type 1 (M.1.1.1)
  - Inter-connect - Type 2 (M.1.1.2)
- SPS Bus Module (M.1.2)
- SPS Frame Module M.1.3)
  - Frame - Type 1 (Long; M.1.3.1)
  - Frame - Type 2 (Short; M.1.3.2)
- Solar Power Generation Module (M.1.5)
- Robotic Arm Manipulator System Module (M.1.7)
- WiFi Router Module (M.1.9)
- Orbital Transfer Ground Infrastructure (M.4.3)

6.0 SPS Kernel Assembly (A.6)

- "Kernel" Core Module (M.1.12)
- Autonomous Rendezvous & Docking (AR&D) System Module (M.1.11)
- Orbital Transfer Ground Infrastructure (M.4.3)

Figure 6 Sketches of Several of the Primary Modules of SPS-ALPHA Mark-II

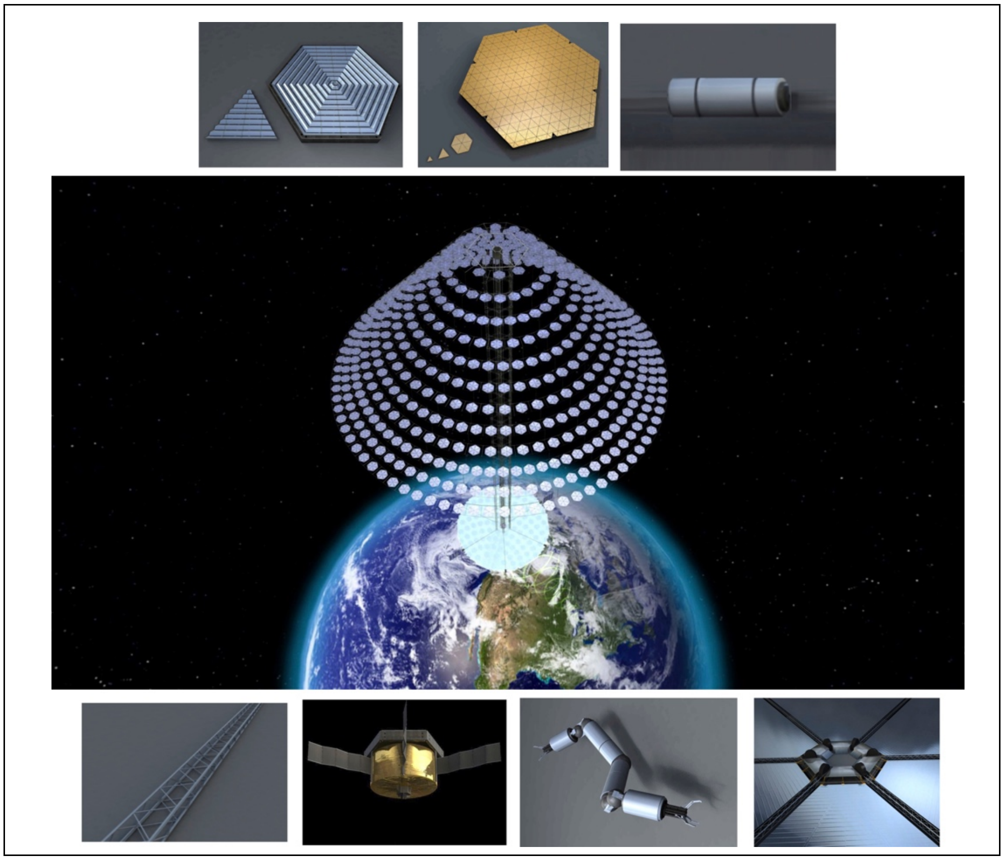


Figure 7 Interrelationships Among SSP Key Performance Parameters

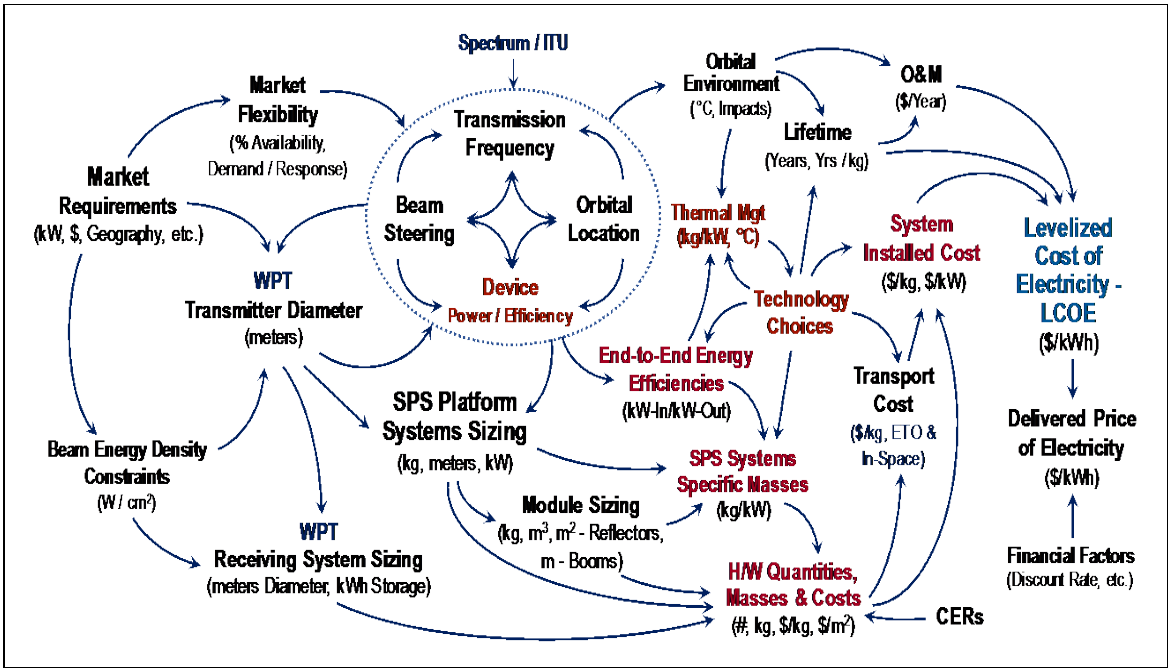


Figure 8 Overview of the Systems Analysis Model

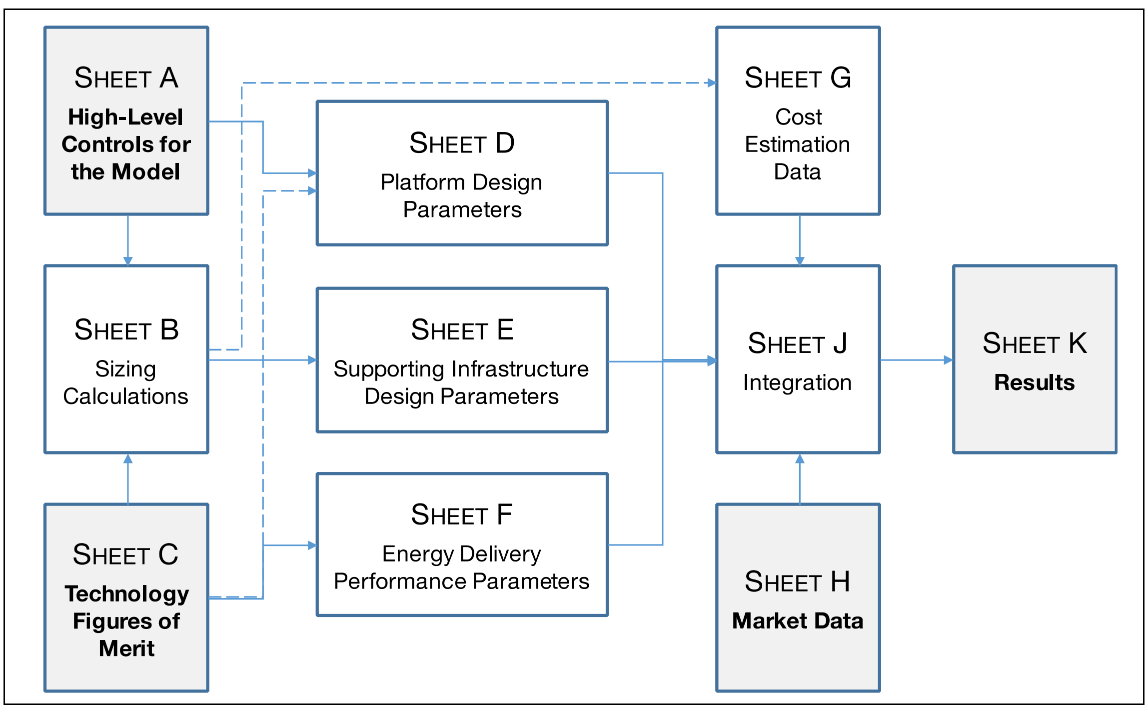


Figure 9 Sensitivity of Results to *Learning Curve* Assumptions

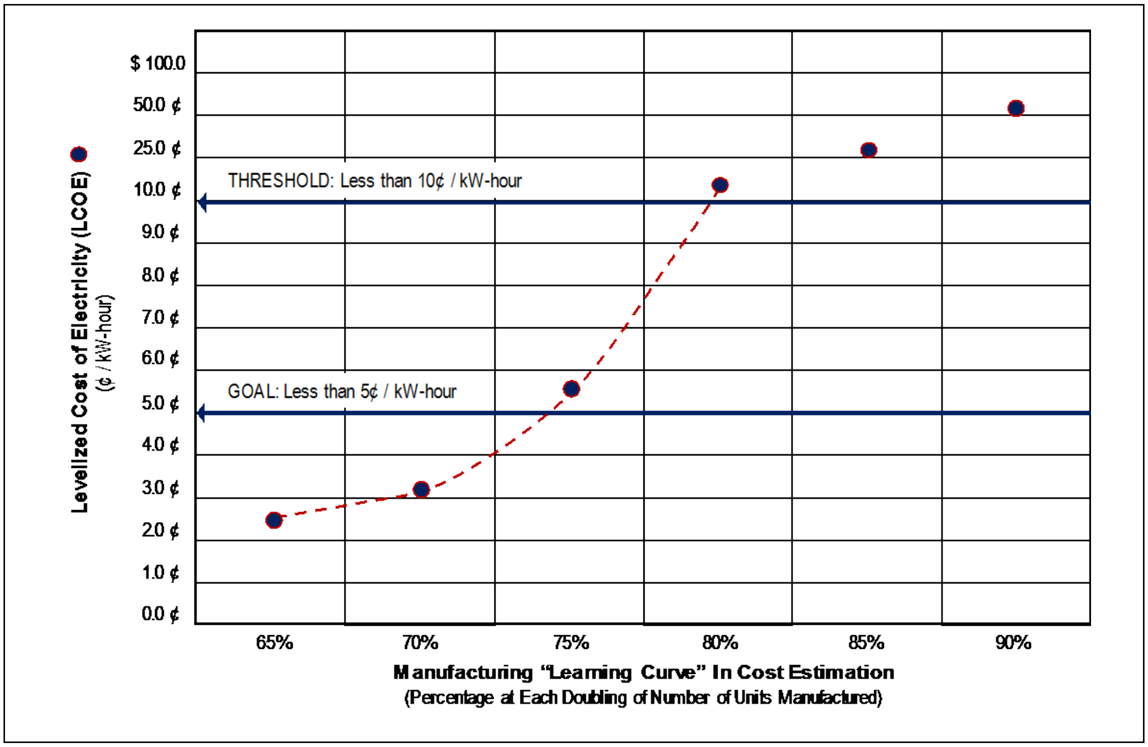


Figure 10 High-Level Ray Tracing for SPS-ALPHA Mark-II

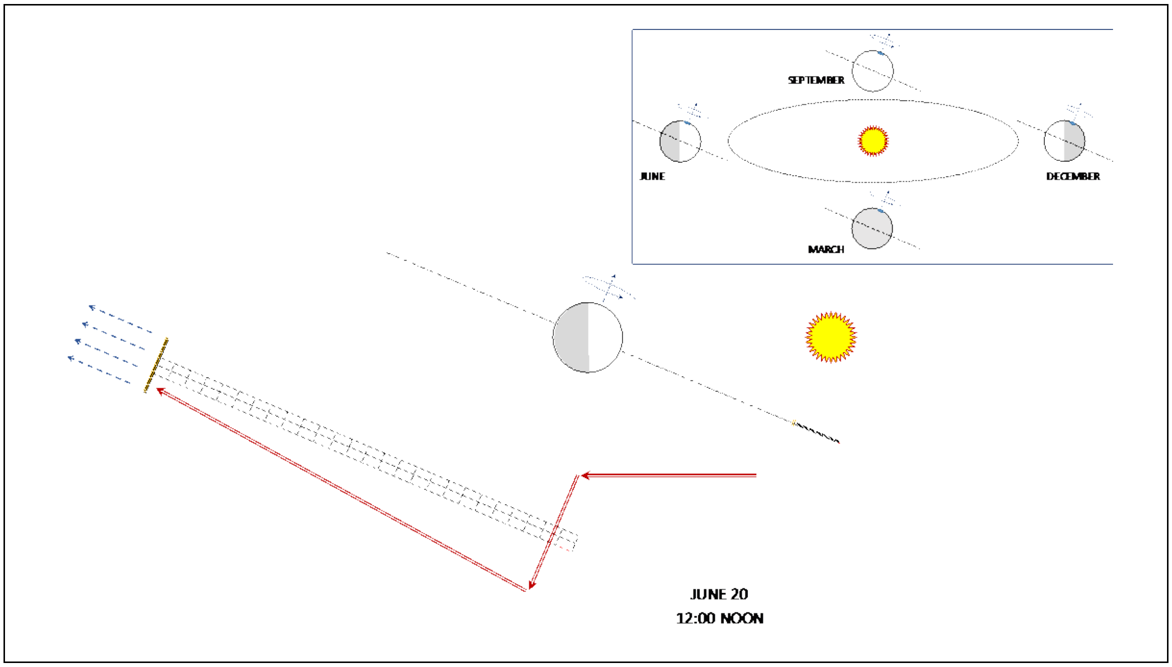


Figure 11 Diagram of the End-to-End Energy Chain for SSP

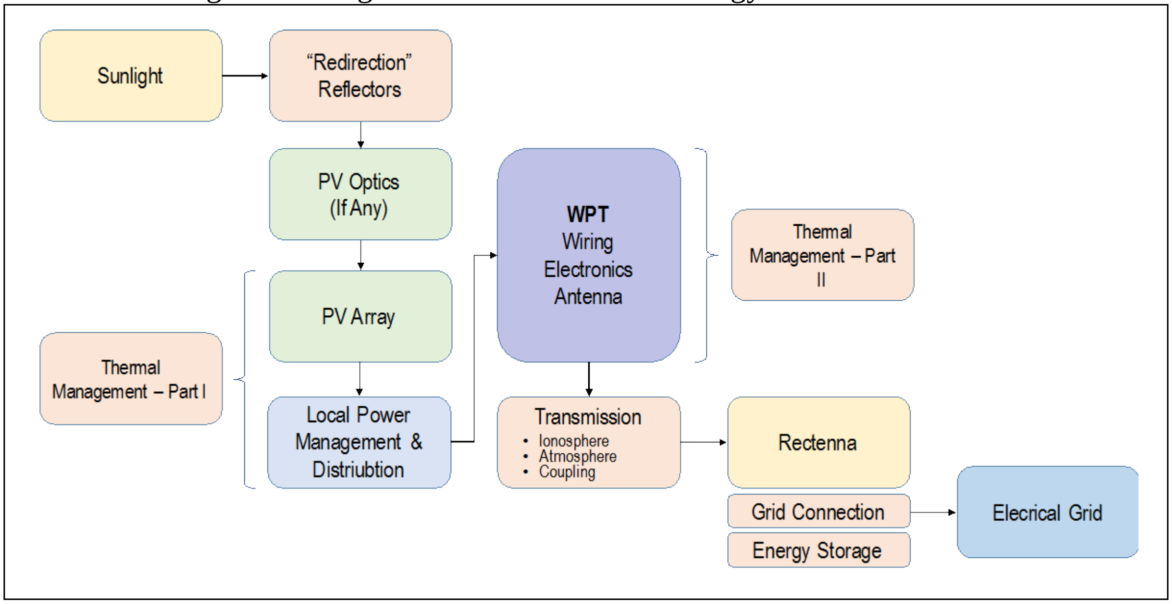


Figure 12 LCOE Sensitivity to WPT Conversion Efficiency

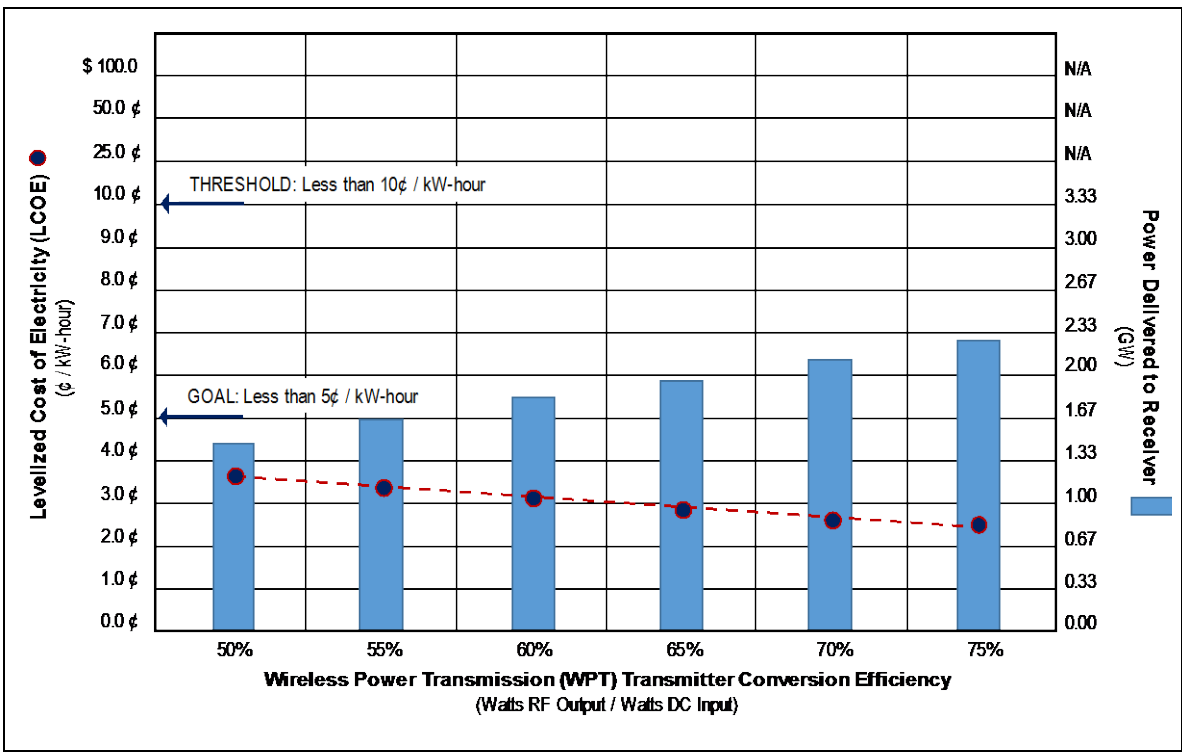


Figure 13 LCOE Sensitivity to PV/Electronics Operating Temperatures

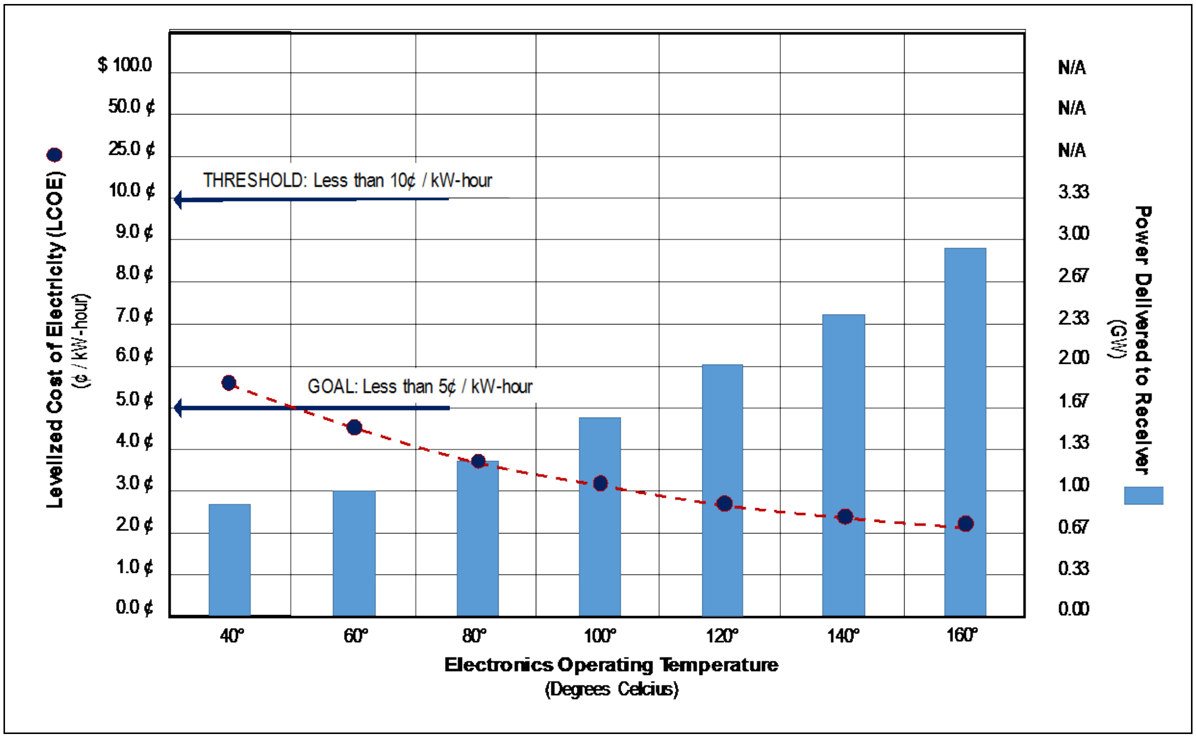


Figure 14 LCOE Sensitivity to ETO Costs

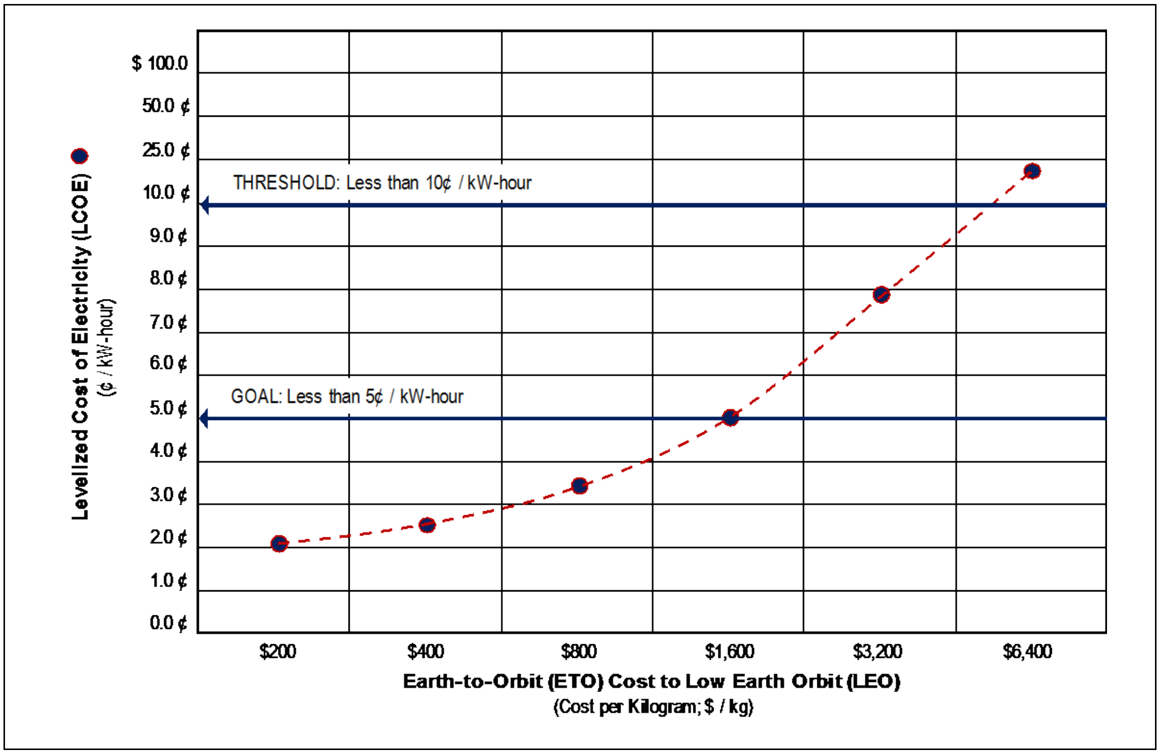


Figure 15 LCOE Sensitivity to SPS Platform Lifetime

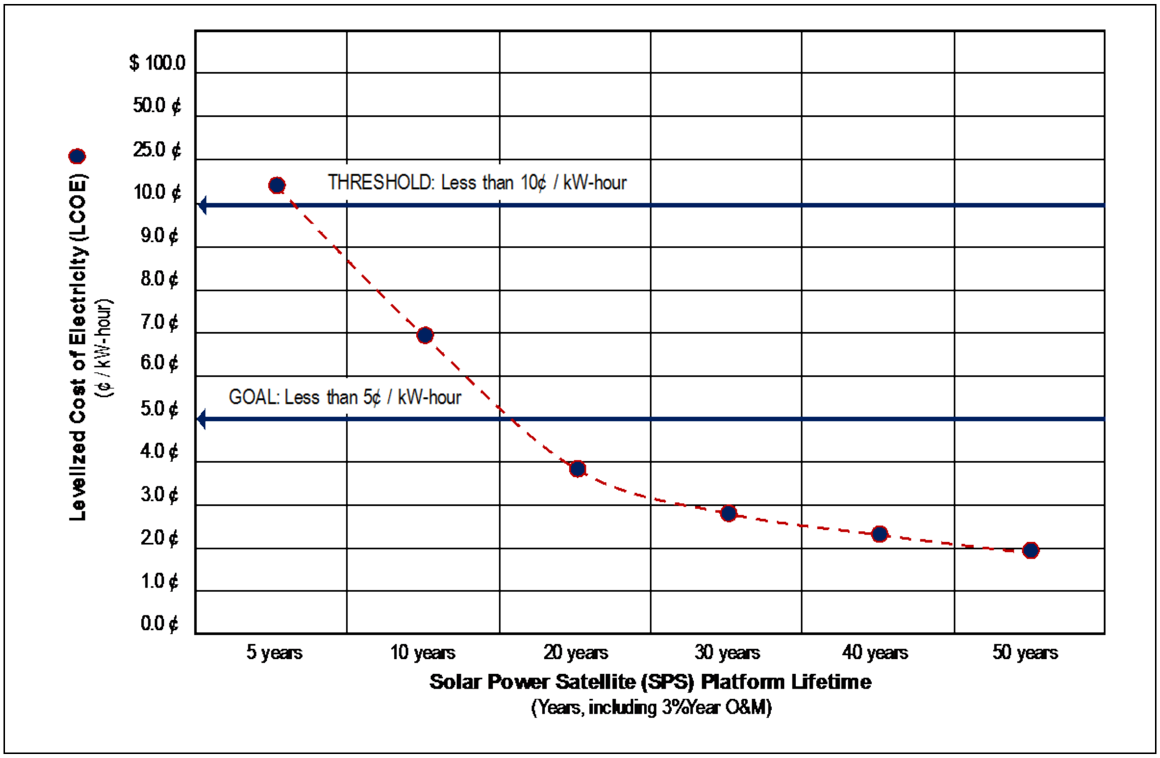


Figure 16 Overall Economics of SPS-ALPHA Mark-II through 2100