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Methodology Report of Cost Benefit Analysis of Space Based Solar Power

Nikolai Joseph[a]*, Jordan M. Sotudeh[b], Marcos Peña[c]

[a] *Office of Technology, Policy, and Strategy, National Aeronautics and Space Administration (NASA), United States,* nikolai.joseph@nasa.gov
[b] *BryceTech, United States,* jordan.sotudeh@brycetech.com
[c] *Office of the Administrator, National Aeronautics and Space Administration (NASA), United States,* marcos.a.pena@nasa.gov
* Corresponding Author

Abstract

Space-based solar power (SBSP) is the concept of gathering power in space and transmitting it wirelessly to users on Earth or elsewhere in space. In recent years, SBSP has seen renewed interest from governments, businesses, and universities for reasons including persistent operations in space, achieving carbon neutrality targets, and more. Several major government agencies in Europe, Asia, and the United States have renewed their SBSP investigations, working with universities and other institutions to advance the technical state of the art. NASA's Office of Technology Policy and Strategy is currently funding a cost benefit analysis of SBSP and comparing it to other sustainable and grid-scale energy sources. This paper presents the study's methodology From these divergent angles the models evaluate fiscal and environmental impacts, identify the state of the most sensitive parameters of the designs, and seek to provide context to leadership on the relative value of pursuing SBSP related technologies.

Keywords: Space based solar power

1. Introduction and Overview

1.1 Overview

Space based solar power (SBSP) is an approach to generating electricity via the collection of solar energy in space, transmission of that energy to the earth's surface, and then conversion of the received energy to electricity. By collecting energy in orbit and transmitting via microwaves or concentrated lasers, SBSP aims to deliver solar energy without significant atmospheric losses. The choice of orbit for the solar power satellites may enable constant coverage of ground receiving stations, providing a potential path for large amounts of clean, continuous power. There are many critiques of SBSP, such as very high upfront costs, especially as the price of renewable energy sources have diminished, and challenges in orbital slots and spectrum allocation. Technical critiques include losses from conversion rates, lack of assembly techniques, industrial immaturity, technology development and manufacturing learning curves, as well as maintenance challenges. NASA's Office of Technology Policy and Strategy is currently funding a cost benefit analysis of SBSP. This paper summarizes the methodology used to make the assessment. Study findings are currently being reviewed and will be available at a later date.

1.2 Brief History

SBSP has long been theorized by space development advocates for it's potential to solve many of the Earth's energy needs and to provide a rationale for space industrialization. First proposed by Peter Glaser of NASA in the late 1960's[1], the concept has evolved in line with technology in the intervening decades. Early SBSP designs were monolithic systems, proposed to take thousands of hours of astronaut time to assemble and maintain. These designs were expensive but offered alternative energy on scales that obviated the need for fossil fuels. These designs matured as the subsystems, such as materials, power processing, solar cells, and launch systems, changed. Large power beaming demonstrations were developed that proved wireless power transmission was physically possible, including a test that beamed power between two Hawaiian Islands[2]. NASA periodically investigated SBSP every decade beginning in the 1970s, going so far to commit to a research program in the late 1990's[3]. While the component technologies and designs changed, the projected overall affordability of systems changed little. Between 1996 and 2016, the proposed specific power (in kilowatts per kilogram), a proxy for performance of an SBSP system, budged little, even as the performance of other space systems improved dramatically (Figure 1: Specific Power of SBSP over time).

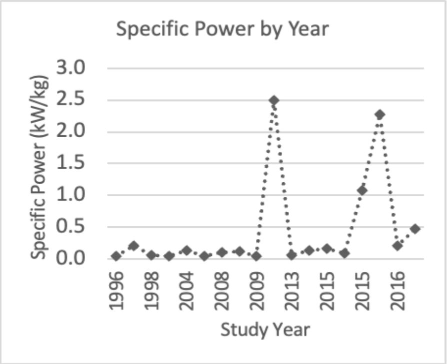

Figure 1: Specific Power of SBSP over time

Through the early 2000's, SBSP systems were largely seen as too expensive, as they would have required many launches, at prohibitively high cost levels per launch. SBSP has not been revisited by NASA in a holistic way since, with the only supportive work consisting of two advanced concept design studies conducted through the NASA Innovative Advanced Concepts program (in 2011 and 2012). These studies formed the basis of one of the designs (SPS-ALPHA Mk III[4]) under consideration in this study. Largely, SBSP was considered physically possible one day, but with many immature subsystem technologies and prohibitive launch costs it remained a very expensive proposition.

Beyond NASA, other nations' space programs[5] developed interests in the prospects of SBSP, both as an energy solution and as a space development approach, including those in Japan, China, India, and the United Kingdom.

While NASA pursued other projects, SBSP was not forgotten by the space community. Technical progress continued in power beaming[6], solar power systems development[7], and many of the other core technologies required by SBSP continued to advance. Widescale miniaturization of electronics, improved robotics systems, and new manufacturing techniques helped change the space sector writ large. The emergence of SpaceX and the advent of cost-effective reusable launch vehicles began to change the scale of possible space systems. While these technologies could change the economic feasibility of SBSP, they cannot change physical realities surrounding the challenges of putting large masses into orbit. SBSP is often proposed and evaluated as a path for broader space industrial development[8], but this study focuses on SBSP as an energy source.

The intertwined nature of space and energy places SBSP in a unique place in the space sector. While advanced space technologies are needed to develop and control an SBSP system, SBSP itself exists to provide energy. Which sector, energy or space, should shoulder the cost for creating and deploying these new systems? This question has inhibited the development of SBSP nearly as much as the technical challenges. While we defer to decisionmakers to wrestle with this question, this study aims to present some conditions to simplify the choices.

1.3 SBSP as an energy source

Dynamic socioeconomic and political conditions have influenced the cost of and desire for SBSP. From 2019-2021[9], electricity demand globally increased by 3.5%, most significantly in China and India (+11.8% and +6.2%, respectively). While historical energy demand has not kept pace with predictions, greenhouse gas emissions from fossil fuel sourced energy has a strong link to the emergent and visible threat of climate change[10]. This has forced some governments to rethink energy policies, including a shift towards the use and development of some renewables[11]. However, fossil fuels still largely power the world economy[12]. The sustainability of this status quo is being called into question and many nations have committed to reducing greenhouse gas emissions and decarbonizing their energy sectors.

Greenhouse gas emissions are a recognized contributor to climate change, electricity generation continues to be one of the biggest sources (~25%[13]). To focus this study, we assess the estimated carbon dioxide emissions generated from building, deploying, and operating an SBSP system. We leave assessment of other greenhouse gas emissions to follow on studies. The Energy Information Agency (EIA) produced an assessment that to reach NetZero by 2050 the United States will need to get approximately 70% of domestic electricity from renewable sources[14]. Further, to achieve the Biden Administration's policy of net-zero emissions by 2050[15], a strong case is present that minimizing lifecycle CO_2 emissions should be an element of any future power mix.

The US in not alone in this. In 2021, the United Kingdom government sponsored a study exploring the use of SBSP to help meet the UK NetZero energy goals[16]. ESA also undertook a cost benefit study to understand how SBSP might help meet European NetZero goals as well. In late 2021, an ESA-sponsored workshop on how SBSP could meet NetZero goals featured nearly 40 speakers from over 20 institutions[17], discussing research and commercial pathways to realize SBSP.

2. Approach and methodology

Given this renewed global interest in SBSP as a means of energy and a motivator of space presence, NASA's Office of Technology, Policy, and Strategy commissioned a cost benefit analysis of SBSP to determine:

A. The feasibility of SBSP based on the technologies available and under development.

B. The role, if any, NASA should have in SBSP development.

First, we define the boundaries of feasibility for this study. Feasibility means the degree of technical, financial, and environmental burden undertaken to deploy an SBSP system as an energy solution. That burden is measured by asking three questions: 1. does the technology exist to build this; 2. how does it compare on cost with alternative energy sources; and 3. how do the carbon costs compare with alternative energy sources?

To answer these questions, a review of the literature on SBSP and survey the literature on national energy mix was conducted. To build the picture of feasibility, a plausible set of use cases was defined (Section 2.1), and a set of applicable energy sources were identified (defined in Section 2.2). To compare across the energy sources a cost metric was introduced (Section 2.3). To assess technical feasibility, existing generic SBSP designs were identified, and subject matter experts assessed the performance required by each subsystem and the performance available today (Section 2.4). To assess the financial feasibility, the same SBSP designs were divided into different development and operational phases, and a cost estimate was conducted on each phase before summing them together (Section 2.5). This cost estimate was varied over several scenarios representing different futures of technology development and translated into a cost of energy metric for comparison with existing alternatives (2.6). To assess environmental feasibility, a carbon cost of the SBSP designs was estimated and a range of carbon costs were projected for each of the scenarios (2.7). The feasibility is holistically assessed in Section 3.

Determining NASA's role takes more factors into account beyond feasibility and will be developed as a follow on to this paper.

2.1 Identifying use cases

To compare SBSP to other alternatives, the scenarios in which they are evaluated must have the same level performance from each system.

While existing energy sources are working to meet demand, energy demand is estimated to increase. Further, in 2018 the Electric Power Research Institute estimated[18] that electrification, "adoption of electric end-use technologies", could increase baseload electricity demand by as much as 50%, by 2050. With US energy demand over 4,000 terawatt hours (TWh) annually presently, the future demand may exceed 6,000 TWh[19]. SBSP has been proposed at many scales, but for a meaningful use case comparison that aims to meet demand, any solution needs to be able to supply power at the gigawatt scale of modern power plants.

Additionally, energy consumption in the modern world assumes constant availability. During the cycle of a day there is a difference of peak versus base load energy usage, with peak demand aligning to cycles of societal activity. Projections for 2050 estimate this daily cycle to require a base load and peak generation of approximately 150 and 250 billion kWh, respectively.[20] This study focuses on supplying base load power generation, as the stable demand for energy is more amenable to analysis. To meet the modern needs of any future scenario, the energy supply must be continuous, or very nearly, over the course of any given year.

An additional caveat is geographic variability. This study is considering SBSP systems in geostationary orbit, where cosine losses from latitude must be considered. Solar power is susceptible to latitude losses as well, and wind availability is contingent on the regional topology. Fossil fuel generation and nuclear are more location independent. To address this, we evaluate energy supplied at two different locations in the US with very different environments: San Antonio, Texas and Philadelphia, Pennsylvania. These cities have similar populations, but differ significantly in their wind availability and solar irradiance. San Antonio is in the south-central plains (29.4°N), with very high solar insolation (irradiance) and stable winds in the plains to the north. Philadelphia is in the northeast coastal region (40°N), with much less solar irradiance and wind availability. While neither of these are extremes in the US, they do represent conditions in which a large portion of the population reside. The variation in cost of producing energy in these different locations capture the effect of geographic variability.

Therefore, to assess how SBSP may fit into a future grid, it must be compared to sources of energy producing 1 gigawatt of base load power, or 24 GWh over a day, continuously, in two different locations.

2.2 List of alternatives

Based on the EIA projections for 2022 and 2050, the most prominent energy sources for US domestic electricity are: coal, natural gas, nuclear electric (fission), wind, hydroelectric, solar (photovoltaic or PV), and solar with storage. Petroleum was excluded because it projects to provide less than 1% of electrical power generation. Considering the uncertainty of availability of SBSP, for comparison we set the 2050 usage and performance estimates for each source.

Brief descriptions for each energy source are presented below.

2.2.1 Fossil Fuels

1. Natural Gas

Natural gas describes a natural combination of methane and ethane produced by the natural decay of organic matter over the course of many millennia. Natural gas is often found oil deposits and can be extracted through wells and piped to plants for compression and distribution as a fuel for power plants.

Natural gas can be liquified at cryogenic temperatures for global transportation at high densities.

2. Coal

Coal is a solid form of fossilized organic plant matter found in large areas of the world. Coal derived energy was a major driver of the industrial revolution and is one of the most widely used forms of energy worldwide. Coal is easily transportable, often moved in open topped rail cars to ports for shipping.

2.2.2 Renewable Baseloads

1. Fission

Fission power is produced by the controlled splitting of high atomic weight atoms, typically Uranium. The fission process releases high energy neutrons which provide heat to a heat exchange system which eventually drives a turbine. Fission power requires the handling and storage of radioactive materials that have significantly higher safety standards than other power sources.

Given public fears about the danger of radioactive accidents nuclear power plants have a very high regulatory hurdle for construction and operation. The hurdles are so significant that the US largely no longer builds them (only two have been built since 2000), instead maintaining old reactors.).

Fission power generation does not produce significant greenhouse gases, nor requires the burning of fossil fuels to function. However, nuclear fuel is very radioactive when it is spent, and the waste needs to be safety handled and stored. This waste may be reprocessed and reused, but the United States does not does this as a matter of custom, instead storing the waste in caverns.

2. Hydroelectric

Hydroelectric power is produced when a dam intervenes with a river, using the force the flowing water to drives turbines to produce electricity. Hydroelectric dams often create a large reservoir of water, and then compress and modulate the flow to maximize the energy production. These reservoirs may alter rivers, disrupt marine wildlife, and impact the livelihood of local populations.

2.2.3 Renewables

Given the inconsistency of sunlight and wind availability, and the lack of an additional "fuel sources", solar and wind power are considered an intermittent and non-dispatchable as these sources do not have the ability to generate power on demand.

1. Solar

Solar power operates by collecting sunlight upon photovoltaic cells (arranged on panels), which convert the solar radiation into electricity. Solar power can be affordably deployed on rooftops and small solar "farms" are placed on open land. Solar power diminishes from peak performance depending on the weather (clouds block sunlight), the season, and the latitude they are deployed. Solar panels do not produce nearly as much power as other sources but on the household scale they can largely meet needs.

2. Wind

Wind power is generated as blowing winds exert pressure on large turbine blades, causing them to turn, and capturing rotational energy in the motor. This energy is converted into electricity for distribution.

Wind turbines are placed on tall towers in regions where wind is both abundant and predictable. These can be on agricultural or rural land, and often are not placed in densely populated areas with buildings that obscure wind flow.

While wind is also intermittent and geographically variable, there is slightly more dispatchability than with solar, as wind power does still generate at night.

2.2.4 Storage

Intermittent power sources must be paired with storage systems to fill in the gaps in service, and the storage options for intermittent energy sources depend on a range of factors.

1. Pumped Hydro

By far the largest energy storage mechanism in the U.S. is pumped hydro, where water pumped up to a higher gravity potential when energy is abundant and released through turbines when demand is high. This accounts for approximately 93% of all stored grid level energy[21]. Much of this is collocated with existing hydroelectric dams, but new capacity is being added (115 MW planned as of 2021).

2. Batteries

Storing solar and wind is largely done with batteries. Residential roof-top solar tends to utilize lithium ion or lithium iron chemistries and are relatively low capacity (10's kWh). Utility grade solar and wind (100's of MW) also utilize batteries. Other chemistries such as molten salt have never reached a level of market penetration they were projected to. Presently, there does not appear to be a strong presence of solar and wind that collocate or directly feed to pumped hydro storage solutions.

While chemical batteries are a present solution, gravity batteries are a technology that is gaining traction as an alternative. Conceptually, they operate similar to pumped hydro in that energy storage comes from moving a mass to a higher gravity potential and is "released" to convert that potential to electricity. This technology is under development still, but existing large scale pilot plants provide reference data that allows for a projection to future operations.

2.2.5 Fusion

While SBSP is often juxtaposed to nuclear, nuclear fission has long been compared to nuclear fusion energy. Fusion potentially offers very high energy output with extremely little waste. While much research has gone into fusion, and many current efforts are underway attempting to capture and commercialize fusion as an energy source, it is not evaluated in this methodology portion. The reason is simple, but underwhelming: fusion offers many of the same benefits as nuclear, at a potentially lower cost, but the feasibility is uncertain. When and should it demonstrate technical feasibility, many of the existing cost estimates may take more value. For now, the study assumes many of the benefits and hope for a lower cost target than conventional nuclear.

2.3 LCOE

A cost metric called Levelized Cost of Energy (LCOE) is used to compare the costs of each energy source to another. LCOE is defined as the cost of a system per unit of energy delivered ($/kWh). This metric is used in energy policy that "combines the primary technology cost and performance parameters: capital expenditures, operations expenditures, and capacity factor."[22] regardless of the amount of power produced. Using the EIA definitions[23], LCOE is calculated as:

$$Levelized\ Cost\ of\ Energy\ (LCOE) = \frac{Capex * \ Fixed\ charging\ rate + Opex}{Capacity\ Factor * 8760\ hours/year} + VOM + Fuel\ Cost$$

Where:

Element	Meaning
Capex	initial capital expenditures to produce the system, per unit of energy generation.
Fixed charging rate	Annualized cost of a capital for the system (similar to a "discount rate")
Opex	fixed annual expenditures for operations and maintenance per unit of generation
VOM	Variable operations and maintenance are expenditure per unit of generation for operations and maintenance
Capacity factor	Maximum fractional portion of the year the system is producing power
Fuel Cost	Expenditures for fuel

Estimates from the National Renewable Energy Laboratory (NREL)[24] for renewables plus storage from its 2022 Annual Technology Baseline were used to estimate performance and cost for of these sources. NREL's coverage of fossil fuels is limited, EIA's numbers in its 2022 Annual Energy Outlook as also considered.

It is worth noting that despite the ubiquitous use of LCOE in energy analyses, no two LCOE sources are calculated with the same assumptions (interest rates and financing, reserves, lifetime, etc.). For consistency, a common source per variable was applied, and noted where each source is used, whether there is any deviation in its application, and why.

2.4 Cost-estimation, sensitivity analysis, and scenario modelling

To estimate costs for an SBSP system, an independent study was conducted by the Aerospace Corporation. Multiple estimates were used for all cost elements and were fed into a cost risk analysis. Analogies to other space system costs were used to establish functional relationships between cost elements and traditional cost estimating relationships (CER). Cost risk analysis was used to estimate appropriate unallocated future expenses (UFE) based on variability of estimates with Aerospace's F-RISK methodology (mathematical approximation to a Monte Carlo simulation). Design Maturity Factor was used in cost risk analysis based upon the state of technology and experience. Schedule risk was converted to a cost using project burn rate. Historical items in the Aerospace Historical and NASA CADRe databases were used as the basis for estimates. Work Breakdown Structure (WBS) element costs and other uncertain quantities were given "probability" distributions. The difference between the 70th percentile and "Most Likely" is UFE. Risk dollars are distributed to individual elements as a function of need.

Each SBSP system was assumed to have a 30-year life space span, with a built-in maintenance and refurbishment cycle.

The Aerospace methodology produced a description of each SBSP system as a series of line items with a range of potential cost estimates. The individual line items of the systems were identified to allow comparison to existing cost models of energy systems, and a 30% "development reserve" was allocated across all elements. The line items fall under three high-level categories: capital expenditures (capex), fixed operating expenditures (opex), and variable operating and maintenance costs (VOM).

Capex includes the cost of space hardware, space transportation (into orbit, to final orbit, and assembly), and the ground receiving land and infrastructure (including spectrum allocation). Opex includes operations of system over its lifetime including retirement and debris mitigation. VOM is the maintenance of the space segment, including replacement and servicing. Each of the expenditure line items include certain assumptions based on if this is the first SBSP system or a marginal one produced, as shown in Table 1.

This study baselined SBSP system costs from a first of a kind (FOAK) starting point to account for as many probable cost inputs as possible and compares that to an evolved "nth of a kind" (NOAK). The FOAK proceeds from what is technologically available today (or very nearly) and assumes limited learning. This bottoms-up accounting approach serves as a conservative assessment of how much it might cost using NASA cost estimating tools as a baseline. While NASA is not in any way proposing to build an SBSP, it establishes a baseline that NASA may assess costs against to determine reasonability of an external design. This is not a proposed cost, but rather a projection of estimated costs, and stresses whether existing aerospace cost modelling approaches could estimate such a unique space system.

Once the FOAK numbers were identified, it was possible to estimate NOAK costs, which serve to estimate the cost of building, deploying, and operating an SBSP system in a commercial sense. These NOAK estimates aim to reduce the first adopter learning penalties that come along with developing a new system. We model several scenarios to represent the learning that might occur over the course of developing a NOAK system.

Scenarios:

- Longer life components (lower replacement rate)
- Deeper learning curve (marginal costs reduce more with economies of scale)
- Retirement of technology risks (technology development removed)
- Commercial development practices (lower management and operations costs)

Other scenarios considered involved robust commercial servicing and in-space tugs for moving between orbits, but there is insufficient historical data to make a reasonable estimate.

Additionally, the NOAK builds in cost learning curves (LC) that represent cost reductions gained from economies of scale and maturation of the component manufacturing sectors. A higher LC shows less learning over time, while a low LC means dramatic learning (and cost reduction) occurs. These LC built NOAKs serve as intermediate data points representing a learning period, whereas a final NOAK is calculated by taking the sum of the FOAK and a large number (100) of the final marginal NOAKs, and dividing by 101.

Drawbacks in this cost estimating approach arise in that extant and historical data may be misleading on work that would be performed more than 5-10 years in the future. For example, although it is not known how much launch costs will decrease, it can be expected there will be some decrease as heavier launch vehicles enter the market. Similarly, the cost estimating team used Northrop Grumman and Aerojet Rocketdyne technology as the basis for estimating orbital assembly costs. This includes the development costs and marginal costs for the Mission Extension Vehicle. For each of these scenarios an LCOE for SBSP is estimated.

By stochastically varying the individual line items within a defined reasonable range a sensitivity analysis will in the final report will identify which portions of the system development may produce the biggest impact on the cost of the system.

	FOAK	NOAK
Lifetime	30 years	30 years
Capex		
Spacecraft hardware	10 year lifetime, 75% LC	15 year lifetime, 5% LC
Mission SE/PM	Baseline	No NRE
Technology development	Included	None
Ground receiver	Baseline	Baseline
Launch vehicle for SBSP	Baseline	60% LC
Launch vehicle for assembly	Baseline	60% LC
Orbital assembly vehicles	Baseline	60% LC
Debris shielding	Baseline	10% LC
Mission Operations and Data Analysis - Assembly	Baseline	Baseline
Opex		
Acquisition of SBSP replacement/maintenance hardware	Baseline	5% LC
Assembly of replacement/maintenance hardware	Baseline	60% LC
Mission Operations and Data Analysis - Operations	Baseline	Baseline
VOM		
Final debris disposal	Baseline	60% LC
Launch Vehicle for debris removal vehicles	Baseline	60% LC
Debris removal of maintenance material	Baseline	Baseline

Table 1: FOAK vs NOAK

2.5 Carbon intensity

In estimating the potential carbon cost of SBSP architectures, Energy Content modelling[25], [26], estimates full lifecycle carbon emissions for a product. To identify the energy content, the fractional amount of various materials by mass of each input material (in categories such as metals, polymers, glass, etc) were estimated. Using Cambridge Univ. data, that estimate informed the total energy content (in MJ) to produce the materials. The result in total MJ of producing a system was converted into tons of carbon equivalent, which can then be compared across differing scenarios.

These final carbon tonnage numbers may then be used to produce a lifecycle carbon intensity of tons of carbon per MWh by converting MJ to MWh (1 MJ = 0.000278 MWh), and adding any emissions produced by operations or fuel sources per MWh. For example, 1 660MW coal plant is estimated to require 1.765E10 MJ[27]. Given EIA's estimate of coal emissions, that means 571672.86 metric tons of carbon are emitted to create such a power plant. Divide that number by operational hours, assuming a 30-year lifetime, and adding EIA's same estimate of emissions per MWh and produces a "lifecycle" (production + operation) carbon intensity of 2.189 tons of carbon/MWh.

$$\mathit{Lifecycle\ Carbon\ intensity}\ \left(\frac{\mathit{tons\ carbon}}{\mathit{MWh}}\right) = \ (\mathit{Energy\ Content\ of\ system}\ (\mathit{MJ}) * (0.000278\ \mathit{MWh}))/(\mathit{Lifetime}\ (\mathit{hours})) + \mathit{Operations\ Emissions}\ ((\mathit{tons\ carbon})/\mathit{MWh})$$

Energy content was then compared to the carbon intensity of other energy sources from EIA, to give estimated carbon intensity of an SBSP system. This methodology is based on estimates but does not include the energy cost of manufacturing the system. Therefore, it is expected this approach will trend towards an undercount of total carbon intensity. However, it does account for the lifecycle, from mining of raw materials to launches required to finally dispose of the obsolete in-space components. Decommissioning impacts are rarely accounted for in terrestrial carbon intensity assessments. Most carbon intensity calculations only consider operational carbon costs (e.g., EIA, NREL…). Existing academic literature sources inform the Energy Content calculations to build different energy production plants, applying the same MJ to tons of carbon/MWh, for an apples-to-apples comparison. These sources' application of EC estimation were reviewed to ensure the same assumptions are followed. Terrestrial transportation was excluded across all EC estimates. Launch is included for SBSP because the terrestrial transportation to produce said launch vehicles is not included, providing a similar equivalency of estimates.

For ease of calculation, estimates were restricted to carbon, however methods do exist for converting other greenhouse gas emissions to so-called "carbon equivalent," such as the EPA's Lifecycle Greenhouse Gas calculations.[28] The United Nations' 2021 Lifecycle Assessment (LCA) of Electricity Generation Options[29] considers different greenhouse gases as well as other environmental impacts, like land and water use. This is an example of forward work that would greatly enhance understanding of the true environmental impacts of energy production options.

2.8 Framework for comparison

Combining the approaches in subsections 2.4 through 2.7, the comparison of SBSP with existing and future use of alternative energy sources to assess the feasibility of SBSP from development and energy cost as well as carbon impact perspectives and will be provided in a table of results in a follow on paper..

3. SBSP Systems Assessment

The terrestrial energy sources were compared to the space-based alternatives. Two rather mature designs were chosen as the focus: SPS-ALPHA Mark III (Mankins) and the SPS-Tethered[30]. There were many factors that went into choosing these designs. First, they are well understood and presented with sufficient technical detail to make comparisons. Second, they are publicly available, so any conclusions drawn in this study can be scrutinized. Third, they represent two matured options that represent fundamentally different architectural options to provide base-load levels of power. Fourth, they are reasonably generic, such that while they represent archetypal designs than may be evolved without compromising their basic functions. Both systems are large, modular, utilize microwave power transmission, and could potentially provide grid level power.

Further description of each option is below.

3.1 SPS-Alpha

Solar Power Satellite Alpha Arbitrarily Large Phased Array (SPS-Alpha) is a design for an SBSP system that provides utility scale power (GWs) via microwave transmission from geostationary orbit. SPS-Alpha employs millions of loosely structured heliostats to direct and concentrate incoming solar radiation towards a central conversion and transmission module. This design is considered hyper-modular, in that it utilizes millions of identical elements to create a larger super structure. This structure spans over 5 km and requires in space assembly in its final operational orbit.

SPS-Alpha was developed by the SBSP expert John Mankins in the last NASA funded design study in 2012. Since then, it has undergone several evolutions, changing elements of the design and some performance parameters. The Mark III design and characteristics are listed in Table 1.

3.2 JAXA tethered

This design was developed by Japan Aerospace Exploration Agency (JAXA) as a planar array of solar panels, with microwave emitters on nadir side, stabilized by a bus that is held in tension via tethers. This design is also modular in nature and can be expanded or shrunk accordingly, with the reference system structured as ~2 km on each side. The smaller design allows it to be deployed in different orbits, including but not requiring GEO.

The tether design was first published in 2006 and represents a simplified model for an idealized SBSP. The power output is directly proportional to the surface area, rather than any concentrators, exquisite structures, or highly complex control schemes.

4. Discussion

This study uses a combination of techniques to build a bottoms-up cost model and carbon intensity assessment of potential SBSP system to alternative sources of energy in a future grid level scenario. While final numbers are important, it is notable that SBSP is unique in space systems in terms of size and construction requirements. It stresses all the assumptions that make existing cost models work. Many space systems have useful heritage, whereas SBSP has very little.

Although full results have not been published yet, early findings suggest there is significant observational data missing to generate a proper accounting in extant literature, both in terms of the real cost of power generation, as well as in the environmental impact of various space-related activities. This should not be too surprising for system architectures that do not yet exist, however in attempting to address these gaps, we provide indices for increasingly holistic assessments.

5. Conclusions

This paper’s methodologies are widely applicable to SBSP and other architectures and may be leveraged and adapted by the wider community to assess novel and unrealized systems, as well as to compare different impacts of electricity generation options. Results from the application of these methods will be published in an upcoming report.

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