

Space Based Solar Power

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Space based solar power (SBSP) entails in-space collection of solar energy, transmission of that energy to one or more stations on Earth, conversion to electricity, and delivery to the grid or to batteries for storage. Experts in both the aerospace and energy sectors are debating the benefits of SBSP as more organizations globally begin SBSP technology development programs. We conducted a study to evaluate the potential benefits, challenges, and options for NASA to engage with growing global interest in SBSP. We performed a first order lifecycle study of two representative SBSP designs for 2 GW utility-scale power generation that, for the purposes of the study, are presumed to begin in 2050. We assumed baseline capabilities to develop, assemble, operate, maintain, and dispose of the SBSP systems are a mix of capabilities that are above, below, or comparable to capabilities demonstrated to date. We then compared the lifecycle cost of electricity and lifecycle GHG emission intensity of the SBSP designs to alternative terrestrial renewable electricity production technologies. Our findings indicate the SBSP designs may produce lifecycle GHG emissions per unit of electricity that are comparable to terrestrial alternatives, pending further studies of upper atmosphere responses to launch emissions. We find the SBSP designs are more expensive than terrestrial alternatives and may have lifecycle costs per unit of electricity that are 12-80 times higher. Though, we do find cost competitiveness may be achieved if a favorable combination of cost and capability improvements related to launch and manufacturing beyond baseline assumptions can be attained.

I. Introduction

This study evaluates the potential benefits, challenges, and options for NASA to engage with growing global interest in space based solar power (SBSP). Utilizing SBSP entails in-space collection of solar energy, transmission of that energy to one or more stations on Earth, conversion to electricity, and delivery to the grid or to batteries for storage. Experts in both the aerospace and energy sectors are debating the benefits of SBSP as more organizations globally begin SBSP technology development programs. Proponents claim SBSP could deliver large amounts of electricity at competitive prices and with fewer greenhouse gas (GHG) emissions than terrestrial renewable electricity technologies while accelerating development of the space economy. Skeptics say SBSP has no clear development path and would divert billions of dollars from known terrestrial solutions while damaging the environment. While it is generally understood that SBSP is cost prohibitive and technically infeasible today, this study assesses operating SBSP systems in 2050. Part of NASA's mission is to innovate for the benefit of humanity – it is through this lens that the Agency weighs whether and how to support SBSP development.

The study addresses the following questions:

- Under what conditions would SBSP be a competitive option to achieving net zero GHG emissions compared to alternatives?
- If SBSP can be competitive, what role, if any, could NASA have in its development?

To answer these questions, we spoke with more than 30 stakeholders and subject matter experts across the aerospace and energy sectors, reviewed over 100 documents relating to SBSP, developed a model to characterize and estimate the costs and GHG emissions of SBSP under varying technological and economic conditions, and qualitatively assessed challenges to SBSP development.

Using these data sources, we:

1. Generated first-order lifecycle cost and emissions estimates for first-of-a-kind, utility-scale SBSP and compared those with current renewable electricity production technologies,
2. Conducted sensitivity analyses to assess whether a competitive SBSP solution is feasible,
3. Conducted qualitative assessments of challenges, opportunities, and NASA's role,
4. Discussed options for NASA's engagement, and
5. Made follow-on study recommendations.

II. Key Findings

A. Question 1: Under what conditions would SBSP become competitive?

- **System Designs**

We assessed two representative SBSP designs: Innovative Heliostat Swarm (Representative Design One, RD1) and Mature Planar Array (Representative Design Two, RD2), based on existing concepts. The SBSP designs serve simply as point designs for assessment purposes and should not be viewed as endorsements to or by NASA. RD1¹ and RD2² are loosely based on historical, publicly available designs that include recent updates and provide enough data from which to perform a first-order analysis of this kind. RD1 generates power 99% of the year and collects solar radiation by autonomously redirecting its reflectors toward a concentrator to focus sunlight throughout each day. RD2 uses flat panels, with solar cells facing away from Earth and microwave emitters facing toward the Earth. RD2 generates power 60% of the year due to its limited capability to reposition itself or redirect solar radiation toward its solar cells. Each SBSP design is normalized to deliver 2 gigawatts (GW) of power to the electric grid to be comparable to very large terrestrial solar power plants operating today.³ Therefore, five RD2 systems are needed to deliver roughly the same amount of power as one RD1 system.

This study assessed lifecycle cost and emissions based on the following scenario: SBSP systems are developed on the ground in the 2030s and launched to low-Earth orbit (LEO), and then transferred to and assembled in geostationary orbit (GEO) in the 2040s. The SBSP systems are operated in GEO from 2050-2080, by transmitting energy to one or more stations on Earth. Maintenance, which entails developing, launching, and assembling new spacecraft modules, occurs between 2060-2080. SBSP systems disposal operations, which entail developing and launching debris removal spacecraft to GEO to transfer spacecraft modules to a graveyard orbit, occurs between 2060-2085. Figures 1 and 2 show the conceptual operations (ConOps) for RD1 and RD2.

- **Lifecycle Calculations**

We developed a model to calculate the cost and GHG emissions for all aspects of the SBSP reference designs across the full lifecycle of development, assembly, operation, maintenance, and disposal. The calculated lifecycle cost and GHG emissions are for first-of-a-kind systems delivering 2 GW of power to the electric power grid beginning in 2050. At the end of 2022, according to the Energy Information Administration (EIA), the United States had 1,160 GW of total utility-scale electricity-generation capacity.⁴

We calculated the lifecycle cost of electricity and lifecycle GHG emissions intensity for each representative SBSP design using common industry expressions: levelized cost of electricity (LCOE) and Economic Input Output – Life Cycle Analysis (EIO-LCA). The LCOE is the average cost of electricity over a generator's lifetime and is a mainstay of energy sector analyses. The EIO-LCA is an established methodology for estimating first-order emissions intensity of economic activity. LCOE has several limitations. For example, it does not consider the variable value of energy at different locations or times.⁵ EIO-LCA also has limitations. This methodology often uses spend-based metrics to estimate emissions, which assumes a relationship between cost, efficiency, and emissions that may not always align with direct measurements of emissions by economic activity.

Space Based Solar Power

Representative Design One: Innovative Heliostat Swarm Concept

National Aeronautics and
Space Administration



2. Assemble

- Manufacture servicers*
- Launch SBSP modules and servicers to LEO*
- Refuel launchers in LEO for orbital transfer to GEO*
- Assemble SBSP modules in GEO with servicers*
- Perform mission operations and data analysis to assemble*

1. Develop

- Research and develop technologies*
- Manufacture SBSP modules*
- Perform project management, systems engineering, and mission assurance*

3. Operate

- Construct ground facilities*
- Perform mission operations and data analysis to operate during service lifetime*

4. Maintain

- Manufacture replacement SBSP modules and servicers*
- Launch replacement SBSP modules and servicers to LEO*
- Refuel launchers in LEO for orbital transfer to GEO*
- Assemble replacement SBSP modules with replacement servicers in GEO*
- Perform mission operations and data analysis to maintain*

5. Dispose

- Manufacture active debris removal spacecraft*
- Launch active debris removal spacecraft to LEO*
- Refuel launchers for orbital transfer to GEO*
- Transfer all SBSP modules from GEO to graveyard orbit with active debris removal spacecraft*
- Perform mission operations and data analysis to dispose*

Figure 1. ConOps for the Innovative Heliostat Swarm Design Reference One System

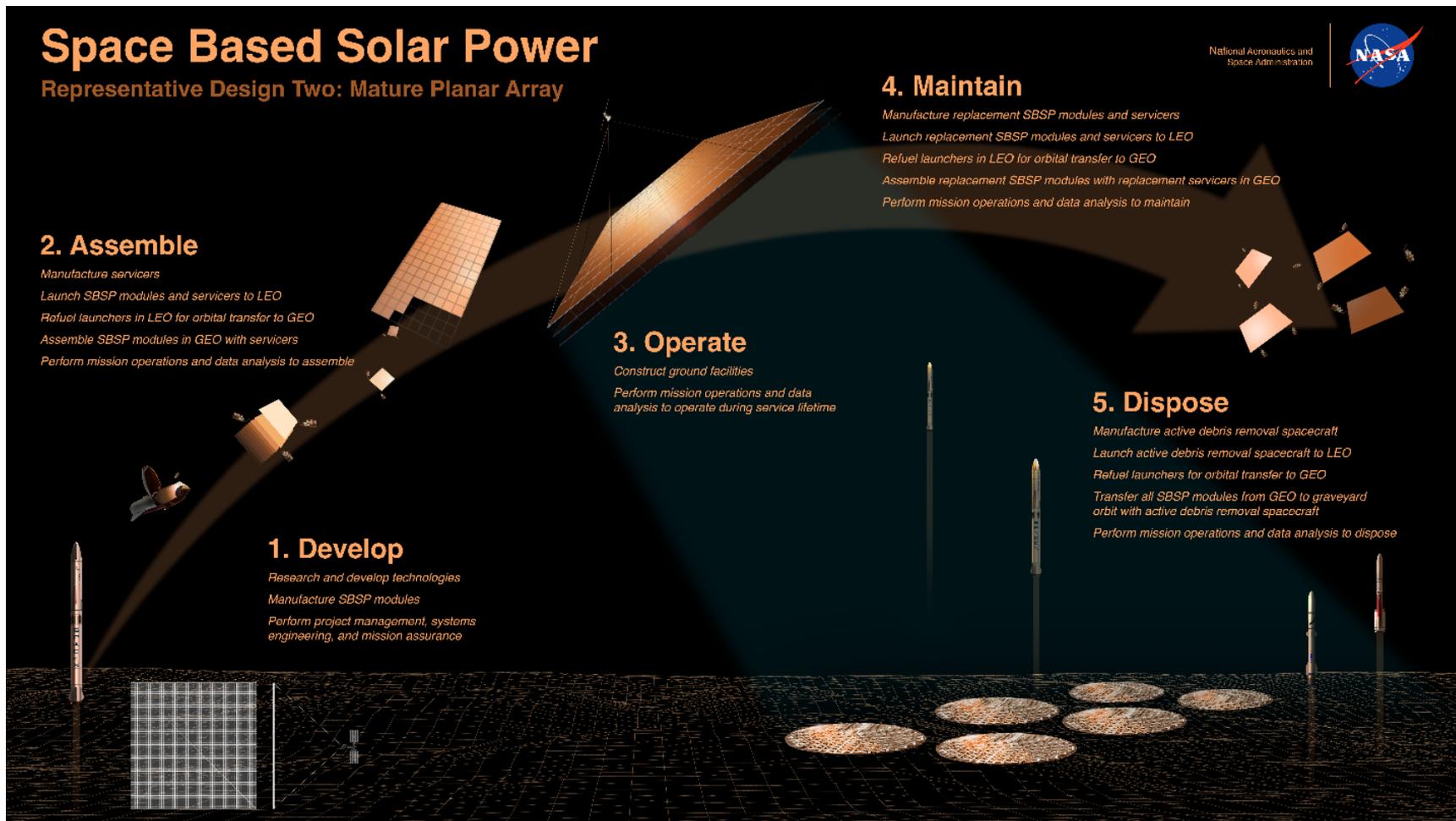


Figure 2. ConOps for the Mature Planar Array Design Reference Two System

All cost estimates are measured in Fiscal Year (FY) '22 dollars. EIO-LCA uses measured GHG emissions of producing goods and services by mass (like kilograms of steel), area (like square meters of solar cells), or cost (like dollars spent on services) by aggregating macroeconomic data. We then compared the LCOE and lifecycle GHG emission intensity (EIO-LCA) to alternative terrestrial renewable electricity production technologies using data from the National Renewable Energy Laboratory (NREL) to assess if the representative SBSP designs are competitive. We compared to NREL's 2050 cost projections and NREL's 2021 median impact lifecycle assessment harmonization of GHG emissions for nuclear fission, geothermal, hydroelectric, utility-scale solar photovoltaics with storage, and land wind without storage. We include land wind without storage for comparison because it has the lowest cost and lowest emission intensity of all electricity production technologies tracked by NREL.

- **Baseline Assessment**

We made assumptions across the full lifecycle of development, assembly, operation, maintenance, and disposal to calculate the cost and GHG emissions of first-of-a-kind SBSP designs. The study's baseline assessment incorporates three assumptions regarding space capabilities: 1) **beyond** assumes certain capabilities will be available by 2050, 2) **comparable** uses today's capabilities as a starting point; and 3) **below** covers the possibility that an existing capability does not perform to previously demonstrated levels when used in a novel SBSP system. We do not include novel architectures or recent advances in material science that may alter the specifications of a 2 GW SBSP system. These assumptions do not represent NASA's position on the future aerospace industry and serve only as an analytical platform.

Beyond: We assume costs to launch a Starship⁶ and reuse each Starship, along with operations costs, are lower in 2050. This is in part because autonomous capabilities are assumed for the representative SBSP designs.

Comparable: We assume solar cell efficiency at the current state of the practice for GEO satellites because technological advances are difficult to predict beyond a few years. We assume an orbital transfer method leveraging refueling launches to reach GEO at the current state of the practice.⁷ We assume manufacturing curves and initial hardware costs at approximately the current state of the practice as a "starting point" for learning over the multi-decade manufacturing process. Manufacturing curves were selected based on analogous industries with similar production levels.

Below: We assume a hardware lifetime below that of the current state of the practice for GEO hardware because the SBSP designs are first-of-a-kind systems requiring multiple refurbishment cycles.

Our study found the following: The baseline lifecycle cost of electricity for RD1 is 0.61 \$/kWh and for RD2 is 1.59 \$/kWh. Launch is the largest cost driver (71% of RD1 and 77% of RD2) as 2,3216 launches are required to deliver 5.9Mkg of mass for RD1 and 3,960 are needed to deliver 10Mkg of mass for RD2. Most of these launches (12 of every 13) serve only to refuel payloads in LEO for transfer to GEO. Manufacturing is the second largest cost driver (22% for RD1 and 18% RD2) and includes initial spacecraft hardware development and manufacturing. Learning curves enable cost decreases over time as experience is gained through producing 1.5M spacecraft modules for RD1 and 2M spacecraft modules for RD2. In general, RD2 is more expensive than RD1 because more mass is involved; five RD2 systems are needed to generate roughly the same amount of power as one RD1 system.

Terrestrial renewable electricity production technologies costs range from 0.02-0.05 \$/kWh. The RD1 LCOE and RD2 LCOE are 12-31 and 32-80 times higher, respectively, than the 2050 projections for terrestrial alternatives. Therefore, our baseline analysis of SBSP designs does not return cost competitive results relative to terrestrial alternatives. For comparison, the average energy cost of a U.S. household in August 2022 was 0.167 \$/kWh.⁸

The baseline lifecycle GHG emissions intensity for RD1 is 26 gCO₂eq./kWh and for RD2 is 40 gCO₂eq./kWh. For comparison, the U.S. electric grid in 2021 produced an average of 385 gCO₂/kWh.⁹ Launch is the largest driver and leads to 64% and 72% of the GHG emissions for RD1 and RD2, respectively. GHG emissions intensity for both RD1 and RD2 fall within the range of GHG emissions intensities (13-43 gCO₂eq./kWh) for terrestrial renewable electricity production technologies. For comparison, the GHG emissions intensities of coal and natural gas are 486 gCO₂eq./kWh and 1001 gCO₂eq./kWh, respectively.¹⁰ RD1 and RD2 emissions intensities do not include upper atmosphere effects of launch emissions, which are assumed to be worse than producing the same emissions on the surface of the Earth, and still under study by NASA and the academic community.¹¹ Our baseline analysis of SBSP designs may have

similar lifecycle GHG emissions intensities to those of terrestrial alternatives, pending further studies of upper atmosphere responses to launch emissions.

- **Sensitivity Analyses**

We conducted sensitivity analyses on the launch and manufacturing assumptions that drive the lifecycle cost and GHG emissions intensity to evaluate what conditions could allow RD1 and RD2 to be cost competitive. We individually varied the following by changing the baseline assumption to a more favorable performance relative to the state of practice: launch costs, first unit manufacturing costs, manufacturing learning curves, hardware lifetime, solar cell efficiency, and orbital transfer methods. A lower launch cost and using electric propulsion to transfer mass from LEO to GEO each reduce the LCOE to about 0.20 \$/kWh for RD1 and to about 0.50 \$/kWh for RD2. This decrease is not enough to make the representative designs cost competitive to terrestrial alternatives. Figures 3 and 4 show the percent decrease in LCOE and GHG emissions intensities from the baseline.

Cost competitiveness can be achieved by varying multiple assumptions at the same time to provide a combination of cost and capability improvements beyond the advances already assumed in the baseline assessment. This favorable combination of assumptions reduces the LCOE to 0.04 \$/kWh for RD1 and 0.08 \$/kWh for RD2 to be cost competitive with terrestrial alternatives. This favorable combination of assumptions also reduces the GHG emissions intensities (3.78 gCO₂eq./kWh for RD1 and 4.33 gCO₂eq./kWh for RD2) to values less than nuclear and wind without storage electricity production technologies. Figure 5 shows the SBSP systems cost (\$FY22) and GHG emissions reduction sensitivities results.

The representative designs may be comparable in cost to and produce less GHG emissions than terrestrial alternatives. The representative designs could become comparable in cost and produce less GHG emissions than terrestrial alternatives if the following favorable combination of assumptions exist in addition to the autonomous operations capabilities, launch capacity, and manufacturing assumptions made in the baseline assessment:

- lower launch cost, \$50M per launch, or \$500/kg; \$425/kg with 15% block discount
- electric propulsion orbital transfer from LEO to GEO,
- extended hardware lifetimes, 15 years
- cheaper servicer and debris removal vehicles, \$100M and \$50M
- efficient manufacturing at scale, learning curves of 85% and below

Our sensitivity analyses highlight the need for advances across a wide range of SBSP enabling capabilities.

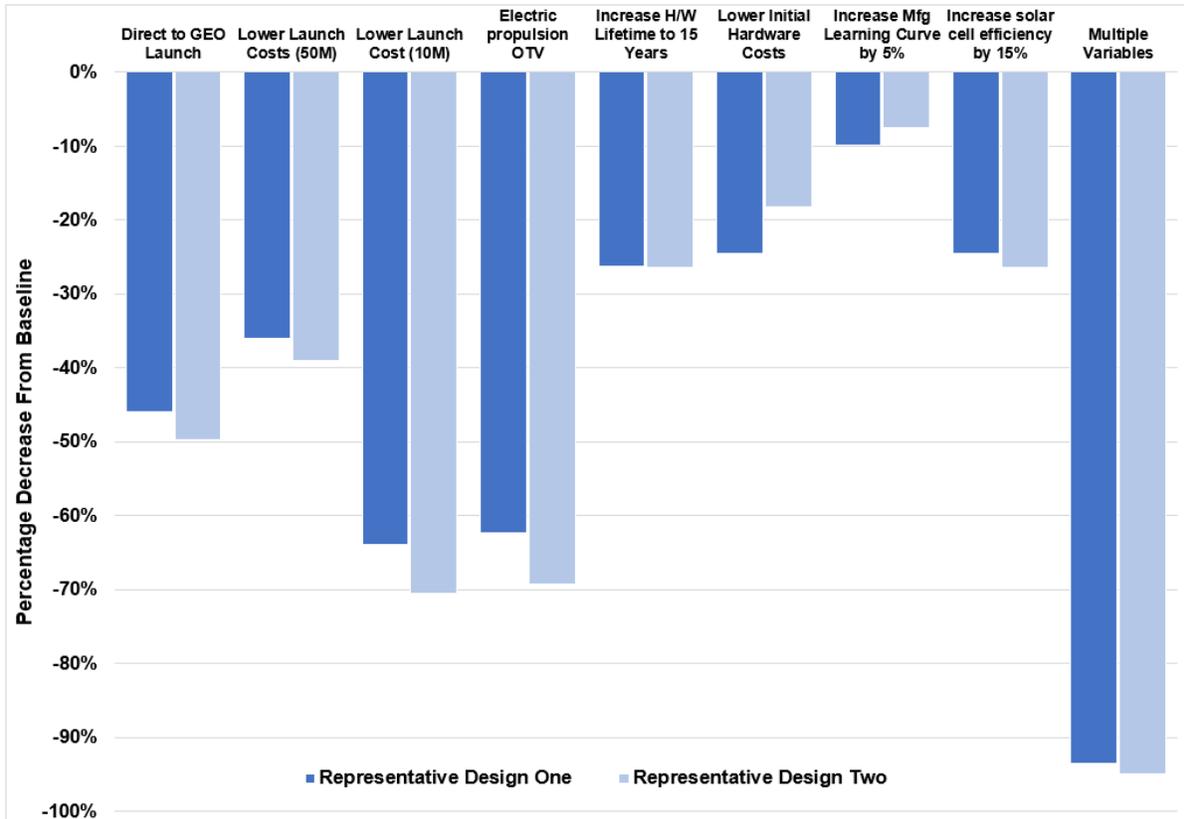


Figure 3. Percent Decrease in LCOE from Baseline

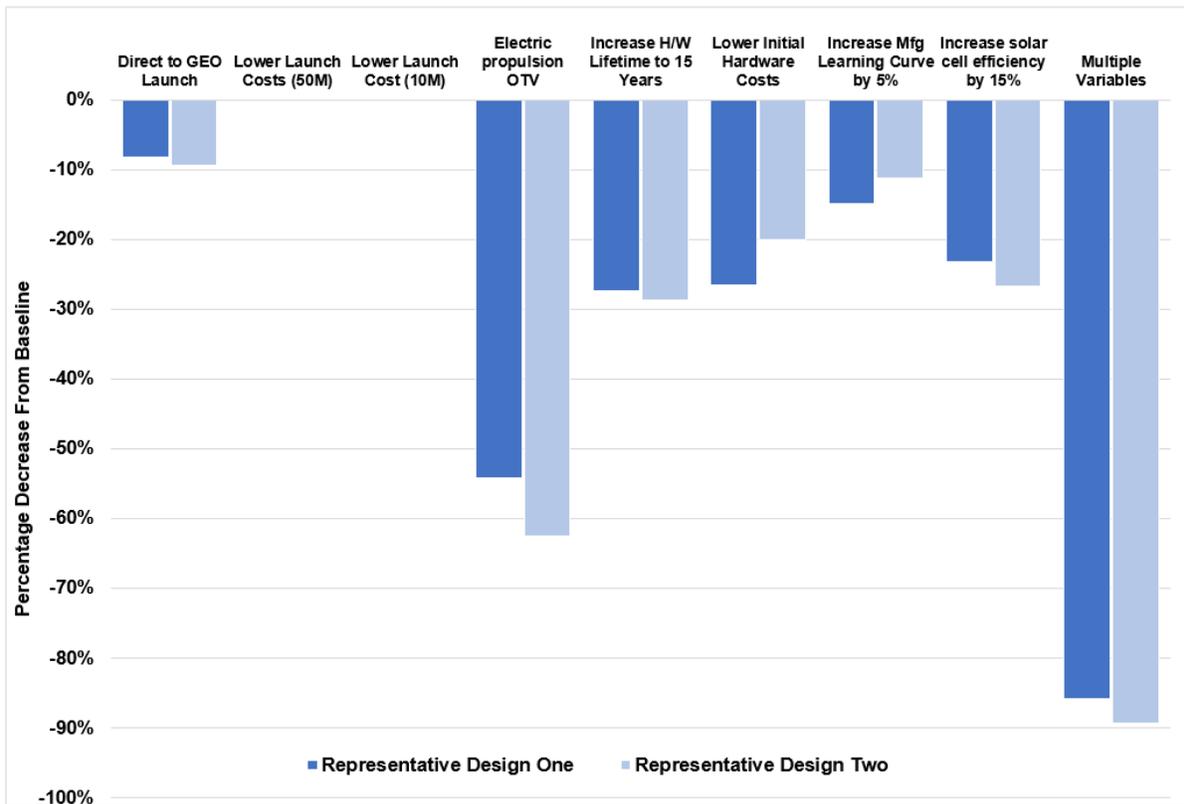


Figure 4. Percent Change in GHG Emissions Intensity from Baseline

maintain awareness of ongoing developments in SBSP. This option does not require any changes to NASA's budget allocations.

2. **Pursue partnership opportunities to advance SBSP:** NASA may find mutually beneficial returns from supporting external SBSP development given the relevance of enabling technologies to other agency missions. Moreover, these technologies, from autonomous operations to wireless power transmission, have many use-cases beyond NASA's missions, and are being pursued by a broad set of public and private actors for many non-SBSP applications.

This study also provides follow-on study recommendations regardless of option choice, including:

1. Building on the first order analysis, study cutting-edge SBSP systems using the most rigorous lifecycle emissions and cost assessments as performed by NREL on other electricity production technologies.
2. Perform a technical design trade evaluation of SBSP technologies for NASA mission applications, such as energy infrastructure on the Moon.

C. Conclusion

We performed a first order lifecycle study of two representative SBSP designs for 2 GW utility-scale power generation that, for the purposes of the study, are presumed to begin in 2050 to determine 1) under what conditions would SBSP be a competitive option to achieving net zero GHG emissions; and 2) assuming SBSP can be competitive, the role, if any, NASA could play in its development.

We assumed baseline capabilities to develop, assemble, operate, maintain, and dispose of the SBSP systems are a mix of capabilities that are above, below, or comparable to capabilities demonstrated to date. We then compared the lifecycle cost of electricity and lifecycle GHG emission intensity of the SBSP designs to alternative terrestrial renewable electricity production technologies. Our findings indicate the SBSP designs may produce lifecycle GHG emissions per unit of electricity that are comparable to terrestrial alternatives, pending further studies of upper atmosphere responses to launch emissions. We find the SBSP designs are more expensive than terrestrial alternatives and may have lifecycle costs per unit of electricity that are 12-80 times higher. However, cost competitiveness may be achieved through a favorable combination of cost and performance improvements related to launch and manufacturing beyond the advancements assumed in the baseline assessment.

NASA is developing technologies and capabilities to meet its future mission needs, such as ISAM and autonomy, which are key enablers for SBSP. NASA could maintain its focus on core Agency missions and technologies, while documenting their relevance to SBSP. NASA may also enhance coordination with U.S. and international partners on technology development with relevance to SBSP. We recommend regular reviews of global SBSP developments and focused analyses of SBSP designs that may enable NASA's core missions.

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- [5] For more information on metrics, see NREL, "Competitiveness Metrics for Electricity System Technologies" 2021, <https://www.nrel.gov/docs/fy21osti/72549.pdf>.
- [6] Due to the size and mass of the representative SBSP designs, for purposes of this study, we used available data from Space Exploration Technologies Corporation's (SpaceX's) Starship launch vehicle because at this time it is

anticipated to be the largest super heavy launch vehicle with data available. The study's use of data from Starship does not indicate any endorsement by NASA.

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