Homeland Defense & Security
Information Analysis Center

HDIAC TECHNICAL INQUIRY (TI) RESPONSE REPORT

Recent Progress in Space-Based Solar-Power Beaming

Report Number:

HDIAC-BCO-2025-682

Completed May 2025

HDIAC is a U.S. Department of Defense Information Analysis Center

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
27-05-2025

2. REPORT TYPE
Technical Research Report

3. DATES COVERED *(From – To)*
2022–2025

4. TITLE AND SUBTITLE
Recent Progress in Space-Based Solar-Power Beaming

5a. CONTRACT NUMBER
FA8075-21-D-0001

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)
Joel Hewett

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Homeland Defense & Security Information Analysis Center (HDIAC)
SURVICE Engineering Company
4695 Millennium Drive
Belcamp, MD 21017-1505

8. PERFORMING ORGANIZATION REPORT NUMBER
HDIAC-BCO-2025-682

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Defense Technical Information Center (DTIC)
8725 John J. Kingman Road
Fort Belvoir, VA 22060-6218

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Statement A: Approved for public release: distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The Homeland Defense & Security Information Analysis Center (HDIAC) was asked to provide information on the status of recent technical demonstrations, research and development, and/or other efforts to advance the field of space-based solar-power (SBSP) beaming. In response, HDIAC partnered with KeyLogic to survey recent efforts that have performed experimental trials or demonstrated the operation of SBSP components or architectures while in orbit and to summarize what technical and economic challenges are currently faced by the near-term expansion and operational deployment of functional SBSP systems for energy industry or military use. To achieve this, KeyLogic and HDIAC reviewed reports and studies from the U.S. Department of Defense, other governmental entities, peer-reviewed academic journals, and comments submitted to HDIAC from members of its network of external subject matter experts.

15. SUBJECT TERMS (PROVIDED BY AUTHOR) solar power, space beaming, space-based power beaming, power transmission, satellite architectures, microwave beaming, optical beaming, radio-frequency beaming, solar collection efficiencies, thermal management, utility-scale solar power

16. SECURITY CLASSIFICATION OF: U			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	SAR	12	Ted Welsh, HDIAC Director
U	U	U			19b. TELEPHONE NUMBER *(include area code)* 443-360-4600

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

About

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A chief service of the U.S. Department of Defense's Information Analysis Centers is free technical inquiry (TI) research limited to four research hours per inquiry. This TI response report summarizes the research findings of one such inquiry. Given the limited duration of the research effort, this report is not intended to be a deep, comprehensive analysis but rather a curated compilation of relevant information to give the reader/inquirer a "head start" or direction for continued research.

Abstract

The Homeland Defense & Security Information Analysis Center (HDIAC) was asked to provide information on the status of recent technical demonstrations, research and development, and/or other efforts to advance the field of space-based solar-power (SBSP) beaming. In response, HDIAC partnered with KeyLogic to survey recent efforts that have performed experimental trials or demonstrated the operation of SBSP components or architectures while in orbit and to summarize what technical and economic challenges are currently faced by the near-term expansion and operational deployment of functional SBSP systems for energy industry or military use. To achieve this, KeyLogic and HDIAC reviewed reports and studies from the U.S. Department of Defense, other governmental entities, peer-reviewed academic journals, and comments submitted to HDIAC from members of its network of external subject matter experts.

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1.0 TI Request

1.1 Inquiry

What is the status of recent technical demonstrations, research and development (R&D), and/or other efforts to advance the field of space-based solar-power (SBSP) beaming?

1.2 Description

The Homeland Defense & Security Information Analysis Center (HDIAC) was asked to provide summary information on recent progress made in the application of SBSP beaming technologies to remotely deliver energy to targets on the Earth's surface. Of particular interest was the potential for transmission to expeditionary military facilities (i.e., impermanent but relatively static tactical locations).

2.0 TI Response

KeyLogic and HDIAC reviewed reports from the U.S. Department of Defense (DoD), the National Academies of Sciences, the National Aeronautics and Space Administration, peer-reviewed academic journals, and online news aggregators focused on the energy and space industries. HDIAC also solicited references and analysis from its subject matter expert network of engineers and scientists working in government, the private sector, and academia.

2.1 Background and Experimental Demonstrations

Research organizations in the U.S. and abroad (e.g., Japan) have explored the feasibility of SBSP systems for decades, to varying levels of success. This section surveys the concept's origins and details how early research has led to a series of recent experimental tests.

2.1.1 Origin of the SBSP Concept

The notion that usable amounts of primary energy from solar radiation could be collected, captured, and transmitted to the Earth's surface dates to the late 1960s [1], coincident with the first use of solar photovoltaic (PV) modules to power manned spacecraft while in orbit (i.e., Soyuz 1 and Skylab). At its core, the SBSP concept is designed to exploit the fact that solar intensity is substantially higher in outer space than below the atmosphere. Efforts to develop, construct, and deploy experimental satellite-based SBSP systems achieved limited demonstrative success from the 1970s into the 2010s [1, 2].

2.1.2 Recent Experimental Demonstrations

A major milestone was reached in 2020, when the U.S. Naval Research Laboratory (NRL), in coordination with the U.S. Air Force, delivered the first testable component of SBSP-enabling hardware into orbit [3]. The module was placed in orbit as part of the Photovoltaic Radio Frequency Antenna Module Flight Experiment (PRAM-FX), a 12-in-square tile. It operated in space until late 2022 and delivered valuable data to NRL scientists regarding its solar capture efficiencies and performance in a low-gravity environment, as well as its response to changes in thermal loads [1, 4].

Within the SBSP community, the success of the PRAM-FX demonstration confirmed a growing sense that the SBSP concept had recently achieved a key milestone in its path to technical maturity. Soon thereafter, similar pieces of SBSP hardware and satellite-related structures were launched into orbit by nonmilitary entities, including a team at the California Institute of Technology (Caltech) in January 2023 [5].

To date, Caltech's Space Solar Power Demonstrator-1 (SSPD-1) appears to have proved itself as a viable multiple in-orbit technical operation that is likely to be critical to the SBSP concept. SSPD-1 addressed knowledge gaps related to the deployment or "unfurling" of large-scale solar arrays, the base feasibility of wireless transmission in the vacuum of space, and the in-space performance of multiple solar PV cell chemistries and types [6].

2.1.3 Upcoming Efforts

Several entities at the national and supranational level have reported plans to launch and test SBSP-related systems in orbit. This group includes, but is not limited to, the European Space Agency (ESA) and groups sponsored by the People's Republic of China (PRC). Multiple commercial entities have also detailed plans to test SBSP satellite equipment and infrastructures in orbit by 2026.

The ESA's initiative SOLARIS aims to investigate the feasibility of an optical, mirror-based system that would direct concentrated beams of solar radiation toward utility-scale solar PV arrays on the surface. The ESA has reported that it will reach a launch decision in 2025 [7].

In early 2025, scientific leaders from the PRC announced an intention to use the nation's recently trialed new generation of heavy-lift orbital rockets to assemble a massive SBSP array of PV cells in a geostationary orbit. This array, with a reported diameter of up to 1 km, would employ microwave-based transmission architectures to export power to specialized receiver equipment located on the ground [8].

Multiple U.S. entities also have notable demonstrations either planned or nominally scheduled for 2025 or shortly thereafter. NRL is developing a follow-on test to its 2020 experiment, known as PRAM-2, to achieve higher in-orbit solar radiation capture, transmission, and end-point reception efficiencies [9]. In collaboration with NRL, the Air Force Research Laboratory, and multiple industry partners, the Space Solar Power Incremental Demonstrations and Research Project intends to launch a demonstration hardware package into orbit in 2025 to test six critical areas of technical operations that require incremental validation to advance SBSP system deployment and use. Known as the "Arachne" flight experiment, this effort will, in part, seek to fill R&D gaps related to thermal management; radio-frequency-based power-beaming operations; and the deployment, stowage, and storage of in-orbit transmission equipment and assets [10].

2.2 Barriers to Operational Deployment

SBSP beaming systems—of any transmission type or architecture—must address many of the same challenges that the concept has faced since at least the 2010s. Whether a system transmits collected energy to the surface via microwave, radio frequency, or laser, SBSP architectures face challenges related to end-to-end efficiencies (i.e., from insolation collection to use on the ground as usable power), human safety concerns, beam interactions with atmospheric phenomena, satellite or solar array stability and persistence in orbit, and the maintenance of effective beam steering and/or turning control during transmission operations.

However, the advancements made since 2020 in orbital tests, experiments, and demonstrations of SBSP components and architectures are, in large part, the result of the weakening of a major challenge to the field—an extraordinarily high-cost burden.

The dramatic reduction witnessed over the past decade in launch costs for U.S. customers has upended the dreary financial calculus behind the generation and transmission of energy from outer space to the Earth's surface. In some instances and for some payloads, launch costs have been cut by a factor of ten [11]. For commercial interests, the recently established consensus within the energy industry that electricity demand in the continental United States will soon witness accelerated growth has only heightened the appeal of SBSP systems that can beam concentrated, efficient solar power into the bulk power system for consumption [12]. The ultimate cost competitiveness of SBSP for terrestrial grid applications, however, is uncertain and contested by experts in the field.

Even so, because the level of capital expenditure needed to develop, launch, and test an SBSP component has fallen so significantly, the field is populated by a dozen or more established R&D groups, military agencies or laboratories, and commercial players. Whether a commercial firm funds its SBSP R&D with an eye to ultimately deriving revenue from the electric utility space, or solely from DoD-funded military applications, the cost thresholds for investments in developing new SBSP technologies and system architectures appears to no longer be a significant barrier to market entry.

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Biography

Joel Hewett is an energy policy and national defense researcher, writer, and analyst for KeyLogic, where he applies more than 15 years of experience in assessing the utility of advancements in science and technology for furthering national aims. In his role, he supports multiple federal agencies in studies addressing energy systems and critical infrastructure protection issues. He is the author of "Resilience by Design: Microgrid Solutions for Installation Energy," a state-of-the-art report published by the Homeland Defense & Security Information Analysis Center. Mr. Hewett holds an M.S. from the Georgia Institute of Technology in the history and sociology of technology and science, where he was the inaugural Melvin Kranzberg graduate fellow, and he earned an A.B. in literature from Davidson College, where he was a John Montgomery Belk scholar.