SPACE SOLAR POWER FOR GLOBAL DECARBONIZATION

Research Prospectus • June 2023 **Technology Innovation**

Unconventional technologies are needed to achieve worldwide decarbonization goals while meeting growing demand for affordable, reliable, secure, and resilient energy. With an eye toward the sky, EPRI is exploring the status and potential of space-based solar as a baseload generation option for terrestrial electricity grids.

TECHNOLOGY INSIGHTS

Space power systems integrate satellite-based solar energy capture and conversion with wireless power transmission to ground-mounted, grid-tied rectifying antennas (rectennas). **Governments and technology developers envision gigawatt-scale space power plants as potentially competitive baseload resources by 2050.**

The space solar concept emerged in the late 1960s as a possible commercial spinoff from the race to the Moon. **Significant NASA investment, spurred by the oil crisis, led to power beaming records achieved in 1975 but not surpassed since.** R&D interest waned due to cost barriers driven by limitations on launch capabilities.

Commercial launch platforms suitable for building large solar satellite arrays now exist, and low-Earth-orbit (LEO) testing of prototype components is under way. Current R&D focused on defense applications of autonomous airborne vehicles and resilient energy networks is advancing long-distance power beaming technology.

Crystalline silicon PV created to power early satellites today supplies low-cost energy to consumers and the grid. **In geostationary orbit (GEO), the Sun never sets, atmospheric losses are zero, and the weather is always clear**. Novel space solar materials and devices are expected to deliver higher efficiency and productivity levels.

RESEARCH QUESTION

PV technology supplies low-cost, carbon-free energy, but solar variability creates needs for backup electricity generation or energy storage.

The Sun shines continuously in space, and current commercial launch vehicles can deliver satellite payloads of unprecedented size into orbit.

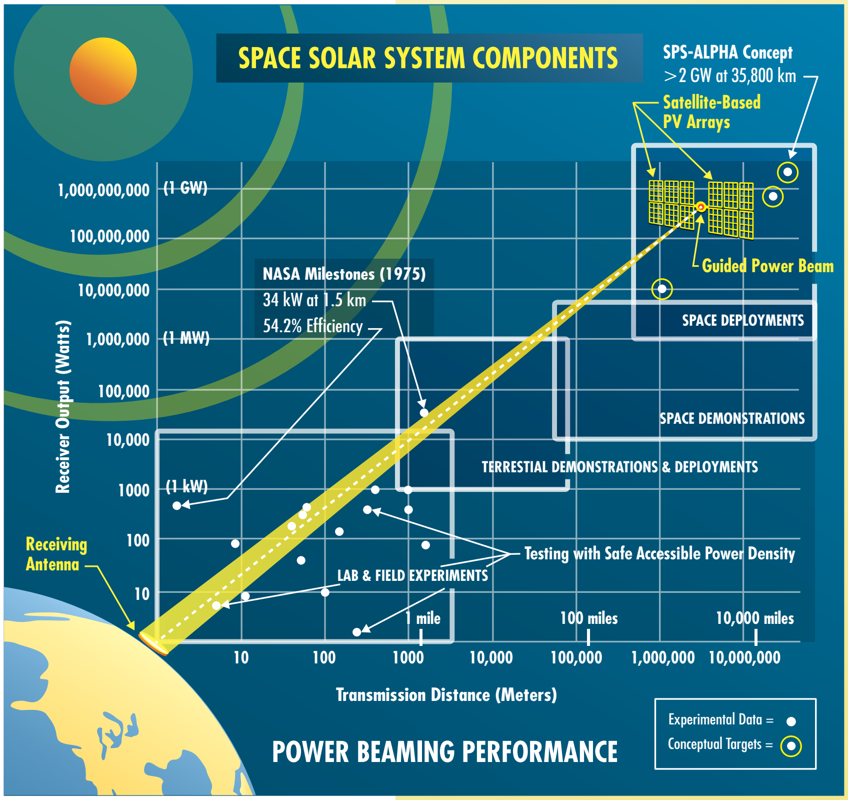
Can space-based solar power plants beaming energy down to the Earth's surface make meaningful contributions to global decarbonization by 2050?

SCALING CHALLENGES

EPRI's 1992 techno-economic assessment identified wireless, satellite-based power transmission as a plausible 21st century solution for serving distant load centers. **As of 2023, challenges to space solar revolve around scale-up of components and integrated systems—first for terrestrial uses, then in space—** to enable safe beaming at grid-relevant power levels over distances of hundreds to thousands of miles.

» **Space Solar:** Satellite-based systems likely will employ optical devices to focus solar energy on multi-junction thin-film PV cells and modules designed and tuned to maximize electricity production under space conditions. ***Key technical challenges**: fabricating multi-gigawatt arrays in space.*

» **Power Beaming & Ground Reception:** Microwaves, rather than lasers, likely will be used based on safety considerations. Electricity-to-microwave conversion will occur within individual PV modules or at central generators within arrays. Earth-based rectennas, employing guide beams to ensure safety, could be smaller than today's gigawatt-scale PV plants. ***Key technical challenges**: increasing power level, transmission distance, and end-to-end efficiency.*



INITIAL TAKE-AWAYS

Status: Space solar is at a technology readiness level (TRL) of 5 based on LEO validation of lab-scale components. System integration and scale-up demonstration are next steps. Leading R&D groups include space/defense agencies and contractors in China, Japan, US, and UK, plus California Institute of Technology and startups emerging globally. Europe is undertaking a new R&D initiative through the European Space Agency (ESA).

Cost: According to 2022 ESA and UK studies, government investment is essential to de-risk space solar and enable baseload plants deployed from 2040-50 to compete with variable solar and wind and to offer significantly lower levelized cost of electricity than other dispatchable resources over a 30-year lifetime. Cost projections are highly dependent on mass in GEO, putting a premium on R&D to increase power-to-mass (W/kg) ratio.

Safety & Spectrum: Power beaming at 2.45 and 5.8 GHz is efficient and can be done safely, offering low atmospheric losses and the ability to meet international standards for human exposure. However, these microwave frequencies lie within bands used for low-power wireless communications, creating electromagnetic interference risks. Building public acceptance and securing dedicated spectrum for power beaming are additional priorities for space solar commercialization.

NEXT STEPS

EPRI is monitoring space solar developments and exploring potential opportunities for electric sector engagement. This may involve defining owner/operator requirements, developing utility use cases, and demonstrating key components and integrated systems.

SPACE SOLAR TECHNOLOGY TIMELINE AND ROADMAP

This timeline and roadmap are based on "Key Sources" below. Current and future TRLs are consistent with expert assessments, which assume adequate public-private R&D investment for 20-plus years. EPRI has not independently assessed space power TRLs.

HISTORY

Space solar advances from TRL1 to TRL5. Space-based capabilities and components are at lower TRLs, relative to needed orders-of-magnitude increases in beaming power and distance.

- **1941:** Microwave power beaming from space to Earth described by Isaac Asimov
- **1963-64:** Integrated beaming system (100 W over 5.5 m) and beam-powered helicopter flight (10 hours at 15.2 m altitude) demonstrated in laboratory by Raytheon and US Air Force
- **1968:** Integrated space power system with ground rectennas described in *Science*
- **1975:** Ground-to-ground beaming record set (34 kW over 1.5 km) by Raytheon and NASA
- **1987:** Beam-powered plane flight demonstrated (20 minutes at 150 m altitude) by University of Toronto and Communications Research Centre Canada
- **1993:** Power beaming between space-based antennas and rectennas demonstrated by Kobe University, Kyoto University, and Japan's Institute of Space and Astronautical Science
- **2020:** Sandwich tile integrating PV generation and microwave conversion modules demonstrated in LEO by US Naval Research Laboratory (NRL)

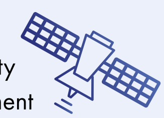
2021 - 2030

Space solar could achieve TRL6-7 as China, European nations, US, and others conduct scale-up validation testing and demonstrate integrated systems on the ground and in space.

Terrestrial Demonstrations & Deployments

- **Ongoing, US Air Force Research Laboratory (AFRL):** Packing, deployment, and assembly of large structures
- **Ongoing, NRL:** Ground-ground, ground-air, and air-ground beaming at greater power levels, efficiencies, and distances
- **2028, UK Space Energy Initiative (SEI):** High-power beaming from stratospheric platform to ground rectenna
- **Pre-2030:** Defense/commercial applications for remote power supply

Space Demonstrations

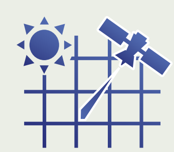


- **2023, AFRL:** Variable emissivity materials for thermal management
- **2025, AFRL & NRL:** Prototype sandwich tiles and beam shaping methods from LEO to ground rectenna
- **2028, China Academy of Space Technology (CAST)** and **2030, SEI:** Integrated pilot-scale LEO systems beaming intermittent power to ground
- **2030, AFRL & NRL:** Subscale LEO systems serving ground bases
- **2030, CAST:** Pilot-scale system beaming continuously from GEO to ground (1 MW)

2031 - 2040

Space solar could advance to TRL8 as integrated systems are launched, lifted, built, and applied to supply baseload power for terrestrial uses.

- **2032-35, SEI:** Pilot-scale system from GEO to ground (500 MW)
- **2035, CAST:** Pilot-scale system from GEO to ground (10 MW)
- **2035, AFRL & NRL:** Full-scale prototype serving ground bases
- **2035-39, SEI:** Full-scale first-of-a-kind plant serving the grid (2 GW)



2041 - 2050

Space solar could achieve TRL9 as industrialized and automated processes enable replicate deployment of gigawatt-scale plants to help meet net-zero targets and global energy needs.

Key Sources: Jaffe, P., (2020). "Power Beaming and Space Solar." Presented at 8th Annual IEEE International Conference on Wireless for Space and Extreme Environments • Rodenbeck, C.T., et al. (2022). "Terrestrial Microwave Power Beaming," IEEE Journal of Microwaves, 2 (1), pp. 28-43 • Rodenbeck, C.T., et al. (2021). "Microwave and Millimeter Wave Power Beaming," IEEE Journal of Microwaves, 2 (1), pp. 229-259 • SEI (2023). "Space Based Solar Power" • Jones, A. (2022). "China aims for space-based solar power test in LEO in 2028, GEO in 2030," Space News • Roland Berger (2022). "Space-based solar power: Can it help to decarbonize Europe and make it more energy resilient?" • OHB (2022). "System breakdown, costs and technical feasibility of a SPS"

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