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Space Solar Power, A Primer on Space Energy

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Executive Summary

Space Solar Power

The notion of collecting power in space was first conceived by Isaac Asimov in his science fiction short story “Reason” in 1941. Then in the 1970s, it began to be taken seriously by NASA and the Pentagon. But its daunting costs put it on hold until the 1990s. Then photovoltaic and solid-state technological advances made the concept plausible. Imagine the power and intrigue of the world’s first orbiting solar farm, unfurled in space, basked in near-constant sunshine, providing a steady flow of power to Earth.

The global electricity market today is currently worth $2.2 trillion and is expected to more than double to $4.6 trillion by 2035. EnerOutlook forecasts that global demand will nearly quadruple from ~8,000 GW to 30,000 GW in 2050. To provide this power, terrestrial solar resources will be key. Space solar power may be complementary, even pivotal, to meeting this demand.

Furthermore, sunshine in space will reach energy-gathering space solar power satellites more than 99% of the time. Space solar power complements terrestrial solar by generating baseload, 24*7 power. Deep space solar collectors will generate power 24 hours a day except for periods of less than an hour each in the 2 - 3 week Spring and Fall equinoxes.

Solar power in space is a very significant and untapped energy resource. The U.S. Department of Energy and NASA began to seriously study space solar power in the 1990s. According to the U.S. Department of Defense, a single kilometer-wide band at Geosynchronous Earth Orbit (35,727 kilometers / 22,200 miles into space) receives 212 terawatt-years of solar power each year. That’s comparable to the energy in all known recoverable oil reserves on Earth today.

The intensity of the sun powering solar power plants in space is ~6 times greater than it is on Earth. There is no atmospheric or cloud interference, there is no loss of sun at night, and there are no seasons. Solar companies will collect solar power in space, some using concentrating mirrors (“light buckets”) made of thin mylar-like films to gather and focus sunlight. These systems will generate photovoltaic power in space, before converting the energy to radio frequencies, and transmitting the energy-laden radio frequencies to Earth.

From Concept to Reality

The basic concept of beaming wavelengths of energy from space has been proven. Different frequencies in the electromagnetic spectrum have been used for their radiating features. Solar-powered communications satellites have beamed electromagnetic frequencies to ground receivers for decades, linking cell phone calls and relaying TV signals to rooftop dishes. Radio frequencies will beam power from space to Earth, a proven technology.

The biggest challenge for space solar power is the cost of launching large solar arrays into space. The weight of the payload is a major factor in the launch of any type of satellite. A 25 MW prototype might weigh ~100 metric tons (220,462 pounds) while a 500 MW plant might weigh over 300 metric tons (661,387 pounds). Such a system might be launched into space using three rockets, one for each the collecting mirrors, the generator module, and the radio frequency transmitter. In the future, 1 – 2 GW plants might weigh nearly 1,000 metric tons (2,204,623 pounds), more than twice the weight of the International Space Station at 450 metric tons (992,080 pounds).

Space is a harsh environment. The equipment has to be thrust into space, fighting the Earth's gravitational field, then unfurled without incident to be ready for flawless operation year after year. Space solar power companies may need to send up small satellites whose mission will be to ensure proper deployment of the arrays, to blow or push components into proper alignment, and/or to provide ongoing observations and maintenance as required.

The Mechanics of Space Solar Power

Space solar power will be collected and then some configurations will use concentrating mirrors to direct sunlight to efficient photovoltaic cells that will convert the sun's energy into electricity. Then solid-state amplifiers will convert electricity into radio frequencies for efficient transmission to Earth.

Most companies envision that their space solar power collectors will be deployed in the Exosphere, 35,727 kilometers (22,200 miles) above the Earth's equator. This is done purposefully to gain the angles and relation of the sun and Earth to be able to be in Geosynchronous Earth Orbit (GEO) and to generate baseload power.

The GEO location of space solar power in the Exosphere dramatically compares with the "Kaaman Line" that delineates the entry to outer space at ~97 kilometers (60 miles). Blue Horizon rockets attain this

altitude. The Starlink network operates at 322 kilometers (200 miles) into space; the International Space Station orbits at an elevation of 402 km (250 miles) above the Earth. Space solar power collectors will be one tenth of the way to the biggest of Earth's satellites: The moon is 384,399 kilometers (238,855 miles) into space.

For over 50 years, satellites have collected solar solar power in orbit via solar cells and have then converted it to radio frequency (RF) energy for transmission to ground receive antennae/stations. This is the same energy conversion process envisioned for space solar power plants. Solid-state power amplifiers will convert the electricity to radio frequencies. Each satellite will be equipped with and use an antenna to direct and transmit the RF power to ground receive stations. On the ground, the RFs will be efficiently converted to electricity.

The space solar power promise is based on being able to beam energy to Earth. Radio frequencies, microwaves, and lasers have all been considered for transmission of energy from space. Microwave transmission research began in the 1960s. By the 1970s, scientists were beaming microwave power up to 1 kilometer (0.62 miles). In 1989, NASA suggested that power could be laser-beamed to Earth using light waves frequencies. Later, lasers were dismissed as their beams would be susceptible to interference and would be too diffuse after transmission from space. In 2008, microwave power transmission was successfully demonstrated in Hawaii, sending energy 148 kilometers (92 miles) between the islands of Maui and Hawaii.

One of the key parameters in beaming power from space is beam spread on the ground and how much land is required to receive space solar power. Lower radio frequencies result in a larger "optical aperture." Higher radio frequencies will be used to avoid interfering with phone signals, and to carry power to Earth, requiring ground receive stations that will initially be ~5.2 square kilometers (1,280 acres / 2 square miles) in area, later down to ~2.6 square kilometers (640 acres / 1 square mile) as the generating antennae become larger.

Addressing Space Junk

Humans have been launching objects into space for more than 50 years. Space junk, more formally referred to as "orbital debris," is defined as any human-made object in orbit that no longer serves a useful purpose, including spacecraft fragments and retired satellites.

As of January 2022, the amount of material orbiting the Earth exceeded 9,000 metric tons. More than 25,000 objects larger than 10 centimeters (3.9 inches) are known to exist. The estimated population of particles between 1 and 10 cm (0.39 - 3.9 inches) in diameter is ~500,000. The number of particles larger than 1 millimeter (0.04 inches) exceeds 100 million.

Most orbital debris resides within 2,000 km (1,243 miles) of the Earth's surface. Within this volume, the amount of debris varies significantly with altitude. The greatest concentration of debris is found in the 750 – 1,000 kilometer (466 - 621 miles) altitude range, far below the likely space solar power locations at 35,727 kilometers (22,200 miles) into space.

Recently, space debris is suspected to have damaged China's Shenzhou 20 spacecraft that was planned to return its three crew members to Earth in November 2025. At the time of this writing, the trio of astronauts that had been manning the Tiangong space station are stranded in space. While a new Tiangong crew has arrived aboard the Shenzhou 21, the China Manned Space Agency has waved off the Shenzhou 20 landing. While details are sparse, experts believe that the likely scenario is that Shenzhou 20 was struck and damaged by a small piece of space debris.

The NASA Orbital Debris Program Office is recognized worldwide for its initiative in addressing orbital debris issues. Russia, China, Japan, France, and the European Space Agency have all issued orbital debris mitigation guidelines.

There are currently over 11,000 satellites in space and this number is expected to rise dramatically in the coming years. Most of them are in Low Earth Orbit (LEO), less than 1,931 kilometers (1,200 miles) in altitude. This is far below the likely position of space solar power plants which will be at an elevation of 35,727 kilometers (22,200 miles) above the equator in Geosynchronous Earth Orbit (GEO). GEO is a special and regulated natural resource. GEO spacecraft operators are required to boost aging spacecraft into higher, disposal orbits at the end of their missions.

Environmental Impacts

Space solar power's conversion process can be carbon-free. Space solar power will be able to generate no greenhouse gases or emissions either in space or on Earth. As such, one U.S. developer of space solar power has been granted eligibility for Renewable Portfolio Standards by the California Energy Commission.

Space solar power plants are not thermoelectric and thus they do not create heat, boil water, or make steam to turn a turbine and generate electricity. No water is required for space solar power generation as it does not need power generation cooling processes.

Space launch vehicles will place the solar power satellites into orbit. These launch vehicles primarily use liquid rocket propellants such as liquid hydrogen (LH2) and liquid oxygen (LOx). Much like fuel cells, many of the rockets that will be used will only exhaust water vapor.

The construction of space solar power plants will have minimal impacts to the environment on Earth. Receiving panels will be ground-mounted at 640 – 1,280 acre locations. Construction of space solar power ground receive stations will have no more environmental impact than the construction of a similarly sized terrestrial photovoltaic solar power plant, while space solar power will generate far more power. The ground-receive antennae will be cited to minimize new transmission lines.

Solar panels on Earth are generally warranted for 25 years with specific degradation rates. Proprietary solar-collection designs for space solar power will likely extend that lifetime to ~30 years by using special collectors that capture and direct to a generator where the sunlight will be converted to electricity, turned into RFs and beamed to Earth.

As with terrestrial photovoltaics, there will be some system degradation, but the photovoltaic generators will be largely shaded by the collectors, minimizing degradation. Thus, the space solar power 30-year lifetime is primarily dictated by the finite amount of propellant fuel on the satellites.

Outer space is regulated by the United Nations. All satellites have to be licensed and must make provisions for being removed from outer space, potentially using solar-powered thrusters and propellant-fueled boosters for end-of-life maneuvers to push the arrays far deeper into space.

Introduction

Collecting Solar in Space

Why go to space? First, terrestrial solar has the huge disadvantage of being an intermittent renewable resource. In contrast, space solar power is baseload power. If you set arrays far into space – in Geosynchronous Earth Orbit (GEO) – the sun never quits. Sunshine is 24*7 22,200 miles from the Earth's Equator. This is done purposefully to gain the angles and relation of the sun and Earth to be able to

generate baseload power. In space there is no weather, no clouds, no water vapor, or seasonality. Space solar power is six times more intense than sunshine on Earth.

Beaming Power to Earth

For over 50 years, satellites have collected solar energy in space via solar cells and converted it to radio frequency (RF) energy for transmissions to antennae on Earth, known as ground receive stations. This is the same energy conversion process that is envisioned for space solar power (SSP) plants. Solid-state power amplifiers will convert the electricity to radio frequencies. Each space solar power satellite will be equipped with and use an antenna to direct and transmit the RF power to ground receive stations. On the ground, the RFs will be converted to electricity.

The space solar power promise is based on the premise of being able to beam energy to Earth. Radio frequencies, microwaves (a subset of RF Power), and lasers have all been studied intensely for safe and efficient transmission of energy from space. Microwave transmission research began in the 1960s. By the 1970s, scientists were beaming microwave power up to 1 kilometer (0.62 miles). Lasers were dismissed as their beams would be susceptible to interference and too diffuse after transmission from space. In 2008, microwave power transmission was successfully demonstrated in Hawaii, sending energy 148 kilometers (92 miles) between the islands of Maui and Hawaii.

Ground Receive Stations

The use of radio frequencies as a carrier is not new. The electromagnetic spectrum carries radio waves, cell phone and television signals, as well as light and heat. Radio waves can carry electricity too, beaming power from point to point.

Higher radio frequencies are proposed for space solar power transmission to avoid interfering with phone signals while carrying power to Earth. One of the key parameters in beaming power from space is beam spread on the ground. This spread dictates the amount of land required to receive space solar power. Lower radio frequencies result in a larger optical aperture. Initially, and for relatively small solar arrays, ground receive stations may be ~5.2 square kilometers (1,280 acres / 2 square miles) in area, later reduced to ~2.6 square kilometers (640 acres / 1 square mile) as the generating antennae become larger.

The construction of space solar power plants will likely have minimal impacts to the environment on Earth. Construction of ground receive stations will have no more environmental impact than the construction of similarly sized terrestrial photovoltaic solar power plants, while space solar power will generate far more power. The ground receive stations will be cited to minimize new transmission lines.

Baseload Power for 30 Years

Solar panels on Earth are generally warranted for 25 years and are guaranteed to meet production values net of specific degradation rates. Advanced solar-collection designs for space-based applications may extend that lifetime to ~30 years by using special, highly efficient collectors. As with terrestrial photovoltaics, there will be some system degradation, but the photovoltaic generators in space will be largely shaded by the collectors, minimizing degradation. Thus, the space solar power plants' 30-year lifetime is primarily dictated by the finite amount of propellant fuel on the satellites for geopositioning purposes.

The New Space Race

A Variety of Missions

The new space race is on! Perhaps the new "space races" plural is a more appropriate term. Countries around the world, as well as private companies and all manner of organizations, are investing in space technologies… with plans for satellites, to go to the Moon, and even to colonize Mars. Consider space solar power as one aspect of the space race. Getting to the moon and colonizing Mars are others. The vision to tap into space solar power is shared by many organizations.

Rockets to accomplish these lofty ambitions are getting larger and stronger, while innovations such as re-usable rockets and refueling in space are capturing imaginations and expanding the possibilities. Imagine data centers in space and industries on the Moon.

The United States, arguably, is in a sprint with China. U.S. Secretary of Transportation, Duffy, says that the U.S. must beat China back to the lunar surface. Artemis II is scheduled to take three astronauts around the moon in April of 2026, preparing for subsequent moon landings. Meanwhile the Europeans are taking the first German into space and to the moon. SpaceX is developing a vehicle to complete a moon landing for NASA planned for 2027.

The remarkable pace of innovations and collaboration continues: A European rocket recently launched South Korean satellites. Multiple astronaut rescue missions took place this year… and in one case three Americans stranded on the International Space Station were shuttled home on a SpaceX rocket due to faults in a Boeing vehicle planned for their return trip.

SpaceX has developed and is testing the world's largest rocket, the Starship. Its next flight will be with Version 3, known as the "Super Heavy." This iteration will be able to support orbital flights, operational payload missions, and be capable of propellant transfer… all with an eye toward developing reusable vehicle services to orbit Earth, and to travel to the Moon, Mars, and beyond.

Private companies are highly active in the space race. The private Firefly Aerospace's Blue Ghost lander touched down successfully on the moon in 2025 and remained operational for two weeks. In February 2024, Houston-based Intuitive Machines put its Odysseus lunar lander down, but it toppled over. It tried again and was successful in 2025 with a second lunar lander called Athena.

The pace of satellite launches is skyrocketing. Just short of 2,700 satellites were launched to space in 2024, bringing the total number of satellites in Earth orbit to 11,539. At the end of 2020, that number was just 3,371.

Moon Shots

The crew of Artemis II is set to blast off from Cape Canaveral, Florida, and after fuel tank leaks were detected, its launch was delayed. It is now scheduled to launch in April of 2026 and to head toward the moon. The mission plan is to swing around the moon and head home. It's the first step in getting man back on the moon for the first time in more than 50 years when Gene Cernan and Apollo 17 landed there in 1972.

Artemis isn't just about planting a flag and collecting some rocks, as it was during the original space race. NASA's ambitious Artemis program has the long-term goal of exploring the moon, with a continuous human presence. And from there on to Mars.

Lunar Nuclear

Russia has plans to build a nuclear-powered energy station on the Moon by around 2036. The project is intended to power a joint Russia–China lunar research base, providing continuous electricity for scientific experiments, robotic missions, and long-term human presence on the moon.

According to Russia's space agency Roscosmos, the lunar power facility would solve one of the Moon's biggest challenges, namely reliable energy during long lunar nights. The Russian nuclear agency Rosatom is involved. It sees nuclear power as the solution to maintaining a colony of people in a place that has roughly 14 days of sunlight followed by 14 days of darkness.

Canada is also involved with the pursuit of lunar nuclear power. The Canadian Space Agency awarded $1 million in funding to the Canadian Space Mining Corporation to develop a low-enriched uranium, micro-mobile nuclear reactor for use on the moon.

Data Centers in Space

Another pursuit involves locating datacenters in space where they can harvest 24*7 solar power. U.S. startup Starcloud recently launched a small satellite carrying an Nvidia processor to run Artificial Intelligence models in orbit, while China has begun deploying a proposed 2,800-satellite system for large-scale orbital computing. SpaceX CEO Elon Musk has said upcoming Starlink V3 satellites could be scaled into orbiting data centers, once Starship is operational. Amazon's Jeff Bezos has predicted gigawatt-scale data centers will be deployed in space within the next decade or two.

Size, Thrust, and Mission Efficiency

Rockets are getting bigger and stronger. The SpaceX Starship is unparalleled in its size and power. It is nearly 400 feet tall. That compares with Saturn V at 363 feet and Falcon Heavy at 230 feet and more than double the Space Shuttle at 184 feet when including its fuel tanks. Starships could be part of NASA's Artemis program that is scheduled to deliver astronauts to the Moon. Artemis 111 is slated for take off in 2027. Its weight when fully fueled is 5,300 tons. It has a payload capacity of 150 tons and it is 322 feet tall, taller than the Statue of Liberty.

Starship is the most powerful launch vehicle ever built: It packs 16.7 million pounds (7,590 tons) of force at lift-off. That compares with the Saturn rocket that took astronauts to the moon with 7.6 million pounds of thrust, less than half of the Starship's capabilities. The Space Shuttle had two solid rocket boosters that have a combined 5.3 million pounds of force at lift-off; Falcon rockets have about 5 million

pounds… both roughly one-third of Starship's thrust. Starship, known as Super Heavy, has 33 engines, each with as much thrust as a 747 Boeing jet.

Leading Initiatives

SpaceX

One of Elon Musk's crowning accomplishments to date, and most promising business ventures, is SpaceX. The company set a new annual record in 2025 by completing a total of 165 orbital launches using the "workhorse" Falcon 9 rocket. Additionally SpaceX launched five suborbital and test flights for Starship in 2025 for a total of 170 launches in 2025, up from 134 in 2024. In 2025, 85% of all American orbital flights were launched by SpaceX, twice the number of missions conducted by China that year.

Space X's founding mission is to carry humans to Mars. SpaceX's goal is to drive down the costs of moving cargo to space cost per pound. SpaceX intends to do this by using "megarockets." Its Starship vehicle is being built to achieve that vision and dream.

SpaceX plans to launch as many as 10 - 24 megarockets per day, up to one an hour. This will be accomplished at Starbase, Texas where SpaceX has sprawling facilities. SpaceX is also building a new launch site at Cape Canaveral in Florida. That process is somewhat more challenging as the Federal Aviation Administration is seeking public input on the new base. Residents there are concerned about disruptive sonic booms that can be as loud as gunshots and that can cause minor damage to buildings. In addition, a nudist recreation group is concerned about potential beach closures.

Starlink Satellites

Starlink is a wholly-owned subsidiary of SpaceX. So far, Starlink has 8,600 active satellites in orbit serving seven million customers with internet service. When Starship is operational, it will haul batches of 60 Starlink satellites on each launch, more than 20 times the number carried on each Falcon 9 rocket launch today. Starship's design features a large slat on the side of the vehicle, a payload door that will open and "spit out" satellites, ejecting them into space.

Recent Developments

Both the Super Heavy rocket booster and the Starship spacecraft are now being designed for reuse, driving down mission costs. Stage separation is when the first stage, the booster, ends its work and comes back to Earth. Prior to disconnect, is "hot staging" when the Starship fires up its own engines

before releasing from the booster. The Booster fires up for 2.5 minutes before upper starship spacecraft ignites its own six engines and breaks away.

It's been a rocky year for Starship test missions as three Version 2 rockets exploded in midflight in 2025. Recently, SpaceX launched its 11th test and successfully completed an hour-long flight. The tests are being used to identify failure points. Starships cruise at 16,000 miles per hour. During reentry, the Starship is designed to be able to heat up to 2,600 degrees F. SpaceX is intentionally pushing the vehicles to their limits, testing different ways to guide the booster home.

Also on the horizon are refueling in orbit and relighting engines in space: Given Starship's size, propellant transfer will be needed as Starship must be topped off with fuel in Earth orbit in order to reach the moon. This orbital refueling has never been done before and is considered a feat. Another feat is relighting engines. Testing has been done with relighting one of Starship's six engines in space. Succeeded with relight tests on Flight 6 and Flight 10 in Nov 2024 and August 2025.

Space Solar Power

Elon Musk is an advocate of space solar power. His Starships are poised to take large payloads of solar arrays into space. Then the power will be beamed back to Earth after being converted to microwaves. To do so, SpaceX is exploring collaborations with partnerships with companies such as Virtus Solis, an Ann Arbor, Michigan-based space energy company.

Blue Origin

Elon Musk and SpaceX are not alone. Jeff Bezos and his space venture Blue Origin, have a vision of enabling a future "where millions of people are living and working in space for the benefit of Earth."

Like SpaceX, Bezos is developing reusable rockets. His BE-3PM was the first new liquid hydrogen fueled rocket engine to be developed for production in America in over a decade. It is carbon free and only emits water vapor. Like the space shuttles main engines, the BE-3PM uses high performance liquid oxygen and liquid hydrogen.

On November 13, 2023, Bezos launched its second heavy-lift, New Glenn rocket, putting two small satellites on a long looping course to Mars. Towering 321 feet tall, the New Glenn rocket has seven

methane burning engines with a combined 3.8 million pounds of thrust. It lifted off from Launch Complex 36 at the Cape Canaveral Space Force Station in Florida.

The New Glenn maiden flight in January successfully lifted into orbit, but its 188-foot reusable first stage failed in its attempt to reach offshore landing ship, Jacklyn, named after Bezos' mother. The second attempt was successful, providing for reuse like SpaceX Falcon rockets.

Amazon Satellites

United Launch Alliance sent another batch of Amazon's internet satellites to orbit on December 16, 2025. Amazon's Low Earth Orbit project was known as Project Kiuper, Amazon's planned satellite internet megaconstellation. This past year, Amazon used the Atlas V rocket to launch 27 satellites from the Cape Canaveral Space Force Station. Amazon's network will eventually consist of 3,200 satellites.

The United Launch Alliance's Atlas V came into service in 2002. It is now being phased out in favor of a number of rockets including SpaceX Falcon 9, Arianespace's Ariane 6 rocket, Blue Origin's New Glenn, and ULA's Atlas V and Vulcan Centaur rockets.

China and Space

China Aerospace Science and Technology Corporation (CASC) is dedicating itself to catalyzing China into a space power, continuously carrying out the national major scientific and technical programs such as Manned Spaceflight, Lunar Exploration, Beidou Navigation and High-Resolution Earth Observation System. It is initiating a number of new major programs and projects such as heavy launch vehicle, Mars exploration, asteroid exploration, space vehicle in-orbit service and maintenance, and space-ground integrated information network. It is also reportedly conducting international exchanges and cooperation, thus making new contributions to peaceful use of outer space.

According to Space.com, 2025 was an eventful year for China in space including reusable rocket tests (and failures), a deep space mission, and the country's first in-space emergency for astronauts. China launched 68 rockets in 2025. It also had the country's first launch and landing attempt of a reusable orbital rocket by which a commercial company Landscape successfully sent its first Zhuque 3 rocket into orbit. China also celebrated three LongMarch rocket launches in a 19-hour stretch.

The Chinese word for astronauts is "taikonauts." The Chinese LongMarch-2F carrier rocket carried the Shenzhou 21 spacecraft with a crew of three. They launched from the Gobi Desert in Northwest China.

Note that China was excluded from the International Space Station project given the U.S.'s concern about the project being controlled by the Chinese government.

China has already landed an unmanned vehicle on the moon. Now, by 2030, the Chinese plan to land its first astronauts on the moon. China also plans to build a lunar base there..

As the leading force of China's space industry and one of China's first innovative enterprises, CASC has eight research and development and production complexes, 11 specialized companies, 13 listed companies and a number of directly affiliated units. CASC is mainly engaged in the research, design, manufacture, test and launch of space products such as launch vehicle, satellite, manned spaceship, cargo spaceship, deep space explorer and space station as well as strategic and tactical missile systems.

CASC's R&D and industrial facilities are mainly located in Beijing, Shanghai, Tianjin, Xi'an, Chengdu, Hong Kong, and Shenzhen. Under the strategy of military-civil integration, CASC pays great attention to space technology applications such as satellite applications, information technology, new energy and materials, special space technology applications, and space biology. CASC also is developing space services such as satellite and its ground operation, international space commercial services, space financial investment, software and information services. CASC is the only broadcast and communications satellite operator in China, and the product provider with the largest and strongest technical strength in China's image information record industry.

CASC is involved in the development of satellites for communication, navigation, and Earth observation. CASC designs and manufactures the LongMarch series of launch vehicles, which have successfully conducted missions including satellite launches and crewed spaceflights. CASC is responsible for China's manned space program, including the Shenzhou missions, which transport astronauts to and from the Tiangong space station.

Russian Rostec

The State Corporation for the Promotion of the Development, Manufacture, and Export of High Tech Products, formerly Rostenkhnologii, Rostec was founded by Vladimir Putin in November of 2007. Rostec's focus is on advancing technology and providing reliable energy sources for space missions and operations. The company's efforts are part of a broader strategy to enhance Russia's technological capabilities and ensure energy independence in the space sector.

Rostec Corporation specializes in advanced industrial technology, particularly in defense, aviation, electronics, and high-tech fields. Rostec is known for its innovations in military equipment, aerospace technology, and energy solutions. It has contributed significantly to Russia's defense and aerospace sectors, producing fighter jets, avionics, and sophisticated radar systems.

Rostec also has been focused on electric vehicle development. The "Atom is a modern, eco-friendly car model" that has been created with support from Rostec State Corporation and KAMAZ. Atom is currently completing the test stage and is being prepared for entering the market, including an electric car presale. The project is based on a proprietary platform with domestic battery, software and digital architecture solutions.

Rostec's Ruselectronics holding company has presented unique electronic components, including quantum microwave devices and traveling wave tubes, designed for the onboard equipment of GLONASS satellites. These components are capable of operating reliably for 150,000 hours in harsh conditions of outer space.

Space Start-Ups

The following bullets highlight a number of diverse space start-ups. They were presented in an EnergyStartUps December 2025 article on the Top 22 Space Startups in 2024 and show the variety of startup ventures in space and their relative funding levels. Two notes: First, some of the startups presented in the article are focused on space energy. Second, the funding levels are self-reported.

- X-energy is a U.S.-based company that aims to produce power systems for lunar bases. X-energy produces small modular nuclear reactors and TRISO-X fuel that can withstand extreme temperatures. It has $1.7 billion in funding.
- Redwire is a U.S.-based company that focuses on space commercialization, digitally engineered spacecraft, on-orbit service, assembly, and manufacturing. It has $450 million in funding.
- Astrobotic Technology is a U.S.-based company that is working to create the first-ever commercial power service for the lunar surface. It will enable space agencies, companies, and nonprofit systems to survive the lunar night and operate indefinitely on the Moon. It has $250 million in funding.
- Antares is a U.S.-based company that designs and builds microfission reactors for strategic energy applications, including space missions, commercial and military energy resilience. The R1

microreactor can produce from 100 kilowatts to 1 megawatt and uses TRISO fuel, which consists of uranium spheres coated with carbon and ceramics, embedded in graphite. Antares has a manufacturing facility in California and has tested its first demonstration unit. It has $126 million in funding.

- Zeno Power is a U.S.-based company that is developing next-generation radioisotope power systems that generate carbon-free, resilient power for decades. It has $95 million in funding.
- Avalanche Energy is a U.S.-based company that is a fusion energy startup that develops micro-fusion reactors that can be used in space. It has $55 million in funding.
- EX-Fusion is Japanese and has been developing a laser-based nuclear fusion reactor for power generation. It has $29 million in funding.
- Star Catcher Industries is a U.S.-based company that claims to be creating an energy grid for space. It has $12.3 million in funding.
- Starpath Robotics is a U.S.-based company with $12 million in fluids spacecraft propellant that reduces the deep space transport cost.
- Zenno Astronautics is a New Zealand company pioneering in superconducting magnets for space applications, a technology that may revolutionize space-movement through the energy of super magnets. It has $6.4 million in funding.
- Above is a U.S.-based company developing technology to provide energy for on-orbit servicing, assembly, and manufacturing. It has $2.3 million in funding.
- Petra Power is a U.S.-based company with the goal of commercializing next-generation solid oxide technology that generates clean, reliable electricity from 8+ fuels while achieving up to 90% reductions in fuel costs and emissions compared to combustion-based systems.
- SunCubes is an Italian company that has the goal to build the future space solar power infrastructure through its innovative satellite recharging system.

Without question, the space race is on and it is multifaceted. Space solar power will clearly benefit as rocket and launch efficiency are improving thanks to stiff competition in the space race and a broad host of ancillary services for the space industry.

Space Solar Power Initiatives

Space Solar Power is an exciting aspect of the space race. Getting to the moon and colonizing Mars are others. The space solar power plant vision is shared by many organizations. What organizations and initiatives are in space solar power? What are their unique selling propositions and/or strengths and weaknesses? While this list is not inclusive, it is intended to illuminate a breadth of initiatives and approaches. The following have, or have had, various forms of space solar power explorations:

Leading SSP Organizations

Airbus (Netherlands)

Air Force Research Lab (United States)

Azur Space GmbH (Germany)

China Aerospace Science & Technology Corp

Emrod (New Zealand)

Frazier-Nash Consultancy (United Kingdom)

Japan Aerospace Exploration Agency (Japan)

Naval Research Lab (United States)

Northrop Grumman (United States)

OHB SE (Germany)

Rostec Corporation (Russia)

SolAero Technologies Corp (United States)

Solaren Corporation (United States)

Space Solar (United Kingdom)

SpaceTech GmBH (Germany)

Thales Alenia Space (France)

Virtus Solis (United States)

Top 10 SSP by Financial Resources

The following table was prepared by Emergen Research in March of 2025 using data for 2024. Note that it is not clear how much of these revenues are spent on space solar power versus other business activities and initiatives.

1.	China Aerospace Science and Technology Corporation	$46,200,000,000
2.	Northrop Grumman Corporation	$40,980,000,000
3.	Rostec Corporation	$31,600,000,000
4.	Air Force Research Laboratory	$2,400,000,000
5.	Japan Aerospace Exploration Agency	$1,460,000,000
6.	SpaceTech GmbH	$645,000,000
7.	Frazer-Nash Consultancy	$161,400,000
8.	Azur Space Solar Power GmbH	$74,100,000
9.	SolAero Technologies Corporation	$22,500,000
10.	Solaren	$2,400,000

Space Solar Power Startups

The following notes on startups come from a list of 22 startups and represent a broad swath of space missions. They are spurred on by a class of space entrepreneurs, developing new technologies to generate and store energy on space stations and spacecraft, to transmit solar energy from space to Earth, and to deliver other energy resources from space. The firms and initiatives presented are focused solely on space solar power.

SolarSpace, USA

SolarSpace is developing concentrated solar power technology at the University of Arizona's Steward Observatory Mirror Laboratory. Its lightweight mirror technology enables large mirrors to focus sunlight on a power conversion unit where it is converted into electricity by highly-efficient, multi-junction solar cells. Patented optics deliver 1,000-fold concentrated sunlight to the cells. SolarSpace has signed a Space Act Agreement with NASA.

Solestial, USA, Funding: $30.1 million

Solestial is aiming to fill the rising demand for solar panels that can withstand the harsh conditions in space while also providing a less costly alternative to what it calls “extravagantly expensive” photovoltaic technology.

EMROD, New Zealand, Funding: $525,200

Emrod uses tele-energy technology to transmit energy wirelessly over many kilometres.

Sparkwing, Netherlands

Sparkwing claims to be an “off-the-shelf solar array answer for the small satellite market.” It produces “an easy-to-integrate” solar array for space applications.

Volta Space, Canada

Volta has built the LightGrid, an orbital architecture transferring power wirelessly to assets on the lunar surface.

Related Space Solar Power Innovations

Overview Energy

Overview Energy has plans to use existing solar farms on Earth to receive solar power from space. It also plans to use laser technology versus microwaves. Microwaves are less sensitive to clouds and humidity than infrared lasers. They can’t transmit in cloudy weather since the suspended water droplets would absorb much of the energy. But because microwave-based systems can’t reuse existing solar farms, they would have to build their own ground stations.

To keep costs down, Overview Energy’s plan is for its ground receiver stations to be smaller, so the energy beams would have to be tighter and more powerful. Companies are developing ways to swiftly interrupt the beam to prevent damage to birds and aircraft, but it’s still a concern.

Overview’s reuse of solar farms would mitigate some of those concerns, though it would still have to convince the public that energy beams from space are safe and won’t stray off target. The company will also have to ensure its laser system is very efficient, otherwise the benefit of collecting sunlight in space will evaporate as the energy is converted to infrared light and back again.

The startup says that in 2028 it intends to launch a satellite into Low Earth Orbit — far below the 22,400 miles at which it ultimately intends to operate. If all goes as planned, Overview Energy will start sending megawatts' worth of power from geosynchronous orbit in 2030.

Reflect Orbital

Engineers and entrepreneurs have floated the idea of space mirrors to send photons of sunlight to Earth for more than a century. In 1923, German rocket pioneer Hermann Oberth proposed the idea in his PhD thesis. It was rejected by Heidelberg University for being implausible. Others envisioned similar projects—to act as a weapon or generate more solar energy—but none came to fruition. In 1993, a Russian satellite known as Znamya 2, with a mirror about 80 feet across, finally made the idea a reality. Its beam, meant to extend daylight hours in Arctic Siberia, was briefly observed across parts of Europe before the craft was intentionally de-orbited.

Reflect Orbital intends to launch thousands of satellites sporting reflective panels—giant space mirrors —into Low Earth Orbit, to redirect the sun's light onto the night side of our planet. The company says this extra sunlight can be used to power solar arrays, assist with search and rescue work, and even fight seasonal depression by extending daylight. Reflect Orbital has applied to the U.S. Federal Communications Commission for a license, saying it plans to begin launching these satellites as early as next year.

Astronomers are concerned about side effects of the project. They're worried that these satellites—each of them with the potential to be several times brighter than the full moon —will hamper their view of celestial objects. They also fear possible risks to ecosystems and to human and animal health.

Reflect Orbital's proposed square-shaped mirrors, made of mylar to boost their reflectivity, would range in size from about 33 to 180 feet across. A prototype mirror called Earendil-1, planned to be 60 feet in length, could launch as soon as April 2026, according to the company's FCC application. The startup intends to send dozens more satellites to space over the next two years, with the aim of putting some 4,000 in orbit by 2030. Last year, the team tested the idea with a large mirror carried aloft in a hot-air balloon, which concentrated a sunbeam onto ground-based solar panels.

Because the satellites will be in Low Earth Orbit, they'll be moving quickly across the sky, with each illuminating a specific patch of ground for only a few minutes at a time. Providing continuous lighting over an extended period will require multiple satellites working in unison—which the company says can be achieved. The beam of light from any particular satellite would be roughly three miles across as it strikes the ground.

Addressing the World Governments Summit in 2025, an annual technology conference held in the United Arab Emirates, the CEO of Reflect Orbital compared his company's ambitions to the ancient invention of irrigation. "This is the first time that humanity is gaining control over the sun," he told his audience. The advancement would be "like when we learned how to control water and move it around so we didn't have to wait for it to rain. We're doing that with sunlight."

American SSP Cohorts

Northrop Grumman

Northrop Grumman Corporation is a prominent American aerospace and defense technology company with a history dating back to its founding in 1939. The company is known for its expertise in space systems, cybersecurity, C4ISR (Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance), and missile defense. It is a key player in the space solar power market, leveraging its advanced satellite technologies and deep-space exploration capabilities to pioneer innovations in renewable energy solutions for space applications.

Notable achievements include contributions to NASA's Artemis lunar exploration program and building the James Webb Space Telescope. Recently, Northrop Grumman has been involved in projects aimed at developing space solar power systems that can transmit solar power from space to Earth, potentially revolutionizing sustainable energy on a global scale. Its competitive advantage lies in its cutting-edge research, extensive defense contracts, and a strong portfolio of space-oriented technologies

In 2015, Northrop Grumman entered into a partnership with CalTech with $12.5 million in funding for the Space Solar Power Initiative. The purpose of the partnership has been to develop ultra-lightweight photovoltaic cells, modular power transmitters, and wireless microwave power transmission from orbit.

Virtus Solis

Based in Ann Arbor, Michigan, Virtus Solis was founded in 2019. Its space solar power generation system calls for large numbers of its satellites grouped into arrays. Each 1.65-meter satellite will deliver 1 kilowatt of power to Earth. Virtus Solis plans to launch a demonstration satellite by 2027, testing in-space assembly and power transmission to Earth.

Virtus Solis plans to launch its system components using SpaceX's Starship rocket. Each Starship will be able to transfer hundreds of the 1.6 meter-wide satellites. Then, 100,000 satellites will be assembled in orbit by robots to form 100 MW solar arrays. The arrays will be in the elliptical Molniya orbit, from 370 - 24,700 miles in altitude, and designed for high-latitude communications. The solar arrays planned will measure one kilometer in diameter. Virtus Solis plans arrays as large as 20 gigawatts.

John Bucknell, PE is the founder and CEO of Virtus Solis, a former SpaceX Raptor rocket engineer, in 2019. He holds 46 patents. Chief Technology Officer, Dr. Edward Tate, has 30+ years experience with analysis and energy systems development and holds 41 patents.

Bucknell believes that when the cost of delivering payloads into orbit falls below $200 per kilogram, space solar power will be more cost-effective than traditional Earth-based energy sources, including nuclear, gas, and coal-fired power plants. SpaceX currently charges $3,000/kg of payload. In the coming years, the use of Starship could reduce this deployment cost. SpaceX anticipates that it will be able to launch satellites into orbit for $10 per kilogram once the Starship becomes fully reusable.

Aetherflux

Space solar power startup Aetherflux is focused on the emerging market for orbital data centers. It joins SpaceX, Amazon, and others exploring ways to move energy-hungry artificial intelligence computing off Earth and into orbit.

Aetherflux announced plans Dec. 9, 2025 to deploy its first Low Earth Orbit (LEO) "Galactic Brain" data center node in the first quarter of 2027, with thousands of proposed satellites slated to follow to improve performance.

The California-based venture aims to be the first commercially viable orbital compute node that would leverage continuous solar power and radiative cooling to support high-density processing in

space. The node would leverage optical inter-satellite links and emerging relay networks to support continuous availability that is comparable to terrestrial servers for these applications.

In 2026, Aetherflux plans to deploy a small satellite designed to wirelessly beam energy from LEO to the ground using infrared lasers. The approach departs from "traditional" space solar power concepts centered on large geostationary platforms transmitting energy via microwaves.

In April 2025, Aetherflux raised $50 million to support its space energy system. The company reports early military interest in its potential to supply energy to remote or contested environments. The U.S. Department of Defense has awarded Aetherflux funds for a proof-of-concept demonstration of power transmission.

United Kingdom

Space Solar

One of the leading European initiatives for space solar power was initiated by an engineering firm called IECL in the United Kingdom, and its lead engineer Ian Cash. Its initiative is called Space Solar LLC and is linked with the U.K's Space Energy Initiative which involves over 80 organizations – such as AirBus – all focused on achieving the country's 2050 zero emissions goal.

The Space Solar website notes that, "For years NASA scientists and aerospace engineers from the world's top institutions have been researching a commercially viable design for a space-based solar power station." Space Solar's Cassiopeia project is well under way with engineering validation done by Frazer-Nash Consultancy. Cassiopeia stands for "Constant Aperture, Solid-State, Integrated Orbital Phased Array." Space Solar's goal is to augment and ultimately replace terrestrial power stations.

One of Space Solar's advances is that it has signed an agreement with an offtaker to take the space solar power that it produces. Iceland's Reykjavik Energy will purchase 30 MW of capacity from the first Cassiopeia array which is slated to be operational by 2030. Space Solar has plans for launching gigawatt sized systems by 2036 and has its sites on offtakers in Iceland, Canada, and Northern Japan. It plans to utilize SpaceX or Blue Origin rockets to propel its arrays into orbit.

China Aerospace

The Chinese see the massive potential for space solar power. The Chinese envision kilometer wide arrays at 22,400 miles from Earth. The CASC space solar power project is considered “another Three Gorges Project” given its massive scale of potential power generation.

Building a giant array in space will take many launches. The Chinese are developing the LongMarch-9 (CZ-9) reusable heavy-lift rocket, which will have a lift capacity of at least 150 tons. Besides being used for satellites, the rocket will also be key to China's plans to reach the moon where it intends to build an international lunar research base by 2035.

China is advancing its space solar power project, aiming to build a one kilometer-wide solar array in Geostationary Orbit by 2050. The Chinese refer to this project as the "Manhattan Project of Energy," highlighting its potential to transform global energy dynamics by harnessing solar energy from space. Like Three Gorges, China’s space solar power project may revolutionize the power sector. Its proponents note that it is as significant as Three Gorges, the world’s largest hydropower project. On the Yangtze River, Three Gorges is 20 times the capacity of Hoover Dam.

China plans to launch a test satellite to demonstrate initial power transmission from Low Earth Orbit, focusing on generating 10 kilowatts of power in 2028. Then by 2030 it plans to deploy a one megawatt solar energy power station in geostationary orbit, aiming for commercial viability. By 2050, CASC plans the completion of a two gigawatt station. These launches will be made possible using the heavy lift rocket, LongMarch-9, aka CZ-9.

Russia: Rostec

Rostec is listed as one of the top ten companies in 2024 in Emergen Research’s space solar power review. It has annual revenues of $31.6 billion.

In the space solar power market, Rostec's strategic focus on cutting-edge space technologies and solar power generation underscores its commitment to energy innovation and sustainability. Recent developments include partnerships aimed at expanding Russia’s capabilities in space solar energy, leveraging Rostec's R&D and manufacturing expertise as a unique selling point to advance national and international energy independence and technology leadership.

Rostec's involvement in space solar power solutions is multifaceted, with a focus on both the development and production of high-tech products for the space industry. The company's efforts related to space solar power are germanium wafers and carbon fiber panels.

Rostec's JSC Germanium has launched the first industrial production of polished germanium wafers, which are used as a base for solar cells in the space industry. These wafers feature higher efficiency and radiation resistance compared to silicon wafers. JSC Germanium, has launched the first industrial production of polished germanium wafers in Russia. Polished germanium wafers are an alternative to silicon ones as they have a higher efficiency than silicon and possess increased radiation resistance and mechanical strength.

Germanium is one of the strategically important rare chemical elements. It is used in high-tech technologies related to space research, solar energy, infrared technology and thermal imaging, electronics, and medicine.

Rostec's Technologiya Research and Production Enterprise has developed a carbon fiber load-carrying panel for a solar module of a promising spacecraft. This panel is the lightest in the world by weight and is 30% more efficient than existing variants. According to Rostec, "Thanks to the use of composite materials, the panel is the lightest in the world by its weight while its high firmness ensures the protection of the module's photocells from cosmic particles, radiation, and space debris."

Japan: Ohisama Project

The pursuit of space solar power is consistent with Japan's vision for a sustainable energy future. Given typhoons, earthquakes, and densely populated areas in Japan, alternative and remote sources of power are particularly attractive and important. In 2011, Japan experienced the Great East Japan Earthquake and the Fukushima nuclear disaster. Space solar power is envisioned to be used during such crises. Japan has been a pioneer in wireless power transmission research, conducting significant ground-based and small-scale orbital demonstrations.

Japan Aerospace Corporation (JAXA) announced that its research and development program will beam power from space in 2025. Its project name is Ohisama which means "sun" in Japanese. In

fact, the term is an honorific and respectful way to refer to the sun. Ohisama was announced at an International Conference on Space Energy in 2024 in London.

Ohisama is a small satellite in Low Earth Orbit that has been orbiting Earth 250 miles above the equator. The satellite is the size of a washing machine. It weighs 400 pounds and its solar panels are 22 square feet in dimension. Ohisama is designed to use microwaves to beam power to 13 ground receive stations in Suwa, Japan. These stations will be ~600 square meters in size, about a fifth of an acre in size. JAXA plans 13 receiving stations over a distance of ~25 miles. Ohisama is considered a stepping stone to 1 GW space solar power stations that JAXA plans. On December 5, 2025, the Japanese reported that Ohisama had delivered “kilowatts” of space energy to Earth.

Beaming Power from Space

Nikola Tesla and Isaac Asimov

The idea of beaming power, the point-to-point transfer of electric energy by a directed electromagnetic beam, originated from Serbian-American physicist Nikola Tesla at the turn of the 20th century. Also known as wireless power transmission, power beaming has become a reality thanks to space and military agencies and increased attention from start-ups and the private sector. Beaming power from space was popularized in 1941 by Isaac Asimov in his sci-fi short story “Reason.” Asimov wrote about humans collecting sunbeams and transferring their power wirelessly to various planets.

Wireless electricity transmission has fantastic potential. Imagine being able to power robots as they move about. How about a helicopter? Consider supplying power to aircraft in flight. In the longer term, consider the opportunity to replace power lines with wireless transmission. Finland has just been in the news for its pursuit of wireless transmission. Imagine no more power lines.

Back to space solar power: Consider powering spacecraft remotely, or inversely, beaming power from space to Earth. Imagine supplying power from space to remote locations on Earth where traditional power cabling is impossible.

The U.S. Naval Research Laboratories' Spacecraft Engineering Division has publicized the benefits of space solar power. "Power plants in the sky" could be used for military operations – installations for forward-operating bases – and for humanitarian missions addressing disaster responses.

Beaming Technologies

Radio frequencies, microwaves, and lasers have each been considered for transmission of energy from space. Microwaves are a subset of radio frequencies.

The radio spectrum is found within the broader electromagnetic spectrum. Radio frequencies (RF) are at the low frequency end of the spectrum, above sound but below light and harmful radiation.

The terms radio frequencies and microwaves are used interchangeably. Radio frequencies have a broad frequency range from 3 kHz to 300 GHz and longer wavelengths, making them suitable for long-distance communication and penetration through materials. Energy from RF current radiates into space as radio waves (electromagnetic waves).

Microwaves are a subset of the RF spectrum and have a frequency range from 300 MHz - 300 GHz. Their shorter wavelengths allow them to travel in straight lines. They are commonly used in radar systems and have a high energy density.

Microwaves

Microwave transmission research began in the 1960s. Famously, in 1964, and on live television, Walter Cronkite demonstrated the use of microwaves to power a model helicopter. It got its power from a microwave beam.

A few years later, Jet Propulsion Laboratory beamed 30 kW for a distance of one mile at 9.5% efficiency. In 2008, microwave power transmission was successfully demonstrated in Hawaii, sending energy 92 miles between the islands of Maui and Hawaii.

One of the issues with the use of microwave beams is spread. One study found that if you beam 1 GW of space solar power at 2.45 GHz, it would require 3.9 square miles on the Earth's surface. For this reason, engineers working to harness space solar power are working with higher frequencies of RF power to lessen the ground receive station size.

While the potential for use of microwaves is apparent, health concerns have also been raised. Microwaves penetrate much deeper into human tissue than sunlight. OSHA limits exposure of microwaves to 10 mW/CM2. At 23 mW/CM2, humans experience learning and cognitive deficits. Another challenge is to beam microwaves without interference or causing harm to existing communication systems on Earth.

Radio Frequency Power

For over 50 years, satellites have collected solar energy in orbit via solar cells and converted it to radio frequency (RF) energy for transmissions to ground receive antennae/stations. Such RF transmission is in the 1 - 10 GHz frequency range and has minimal losses in the atmosphere.

This is the same energy conversion process that space solar power developers plan for space energy plants. Solid-state power amplifiers will convert the electricity to radio frequencies. Satellites' antennae will direct and transmit the RF power to Earth. On the ground, the RFs will be converted to electricity.

One of the key parameters in beaming power from space is beam spread on the ground and how much land is required to receive space solar power. Lower radio frequencies result in a larger "optical aperture," meaning that more land is required.

Imagine the challenges of harvesting and transmitting space solar power from solar arrays in Low Earth Orbit. Satellites at that altitude move at 17,400 miles per hour. Thus beaming their power precisely to Earth is difficult.

Space solar power developers plan to put space energy plants in Geostationary Earth Orbit, 22,400 miles into space. At that altitude, by synchronizing with the counter-clockwise spin of the Earth, the antennae geometry stays constant, and thus the land area required can be smaller.

Lasers

Lasers – Light Amplification by Stimulated Emission of Radiation – are a form of electromagnetic radiation that operate across various regions of the electromagnetic spectrum from ultraviolet to infrared. In 1989, NASA suggested that power could be laser-beamed to Earth using light wave frequencies.

Later, lasers were dismissed as their beams would be susceptible to interference and would be too diffuse after transmission from space. There are other concerns with the use of lasers as well. While they have lower costs, their highly concentrated beams can threaten eye and fire safety. Lasers also create “weaponized concerns” as their “military potential is apparent.”

According to the Harvard Technical Review, September 5, 2025, “Microwaves are generally preferred for transmission because of their capacity to pass through rain and clouds, ensuring reliable energy transmission with minimal loss. An alternative approach involves converting the solar panel electricity into laser light. Despite their potential for narrower beams that allow for smaller receiving stations, lasers are more vulnerable to atmospheric interference and pose a larger safety risk due to beam divergence. The spread of high-powered lasers are difficult to control and can expose unintended targets to intensive radiation, causing human skin burns or damage to sensitive equipment.”

History of Beaming Power

Eighty-four years after being conceptualized in sci-fi, space solar power is now taking root. The United States, China, Japan, Russia, and a number of European entities are all working on harvesting space solar power. China plans to have a working system in the 2030s. Japan launched its prototype at the end of 2025 and claimed that its December 5th demonstration was successful. All parties are working on beaming power from space using wireless energy transmission.

Asimov’s sci-fi notion was first propelled toward reality by Peter Glaser, a former NASA engineer, who filed and received a patent in 1973 for the use of microwaves to bring power from space to Earth (Patent #3,781,647). His design employed very large antennae in space and rectennae (receiving antennae) on Earth. Glaser was at AD Little at the time and NASA paid the firm to do a study of the concept’s feasibility. It identified major problems with harvesting space solar power, notably the expense of launching satellites into orbit. But the study did show enough promise to warrant further research. And in 1975, using microwaves, researchers sent 30 kW for a distance of over a mile with 50% efficiency.

In 1978, Congress directed the U.S. Department of Energy and NASA to jointly investigate the concept of space solar power. Fifty million dollars was authorized before the program was scuttled in 1980 for political reasons. Then in 1997, just shy of two decades later, NASA conducted what is

known as the “Fresh Look” study. It linked nicely with NASA’s Earth to Orbit program designed to drive down the costs of launches.

The Fresh Look ushered in a new era of space solar power research and development both domestically and abroad. The U.S. National Security Space Office recommended a feasibility study in 2007 to investigate solar power satellite technology. In 2012, China and India formed a collaborative effort to study space solar power. A 2014, an IEEE Spectrum magazine article by Susumu Sasaki titled “It’s Always Sunny in Space,” made clear the benefits of harvesting energy in space where there are no atmospheric gases, dust, clouds, or other weather events.

In 2015, Japan transmitted 1.8 kW for a distance of 55 meters; then 10 kW over 500 meters. Then in 2019, PowerLight showed off laser power beaming at the Port of Seattle. Later, in 2024, the U.S. Naval Research Laboratories (known for its development of GPS) sent 1.6 kW via microwaves across a kilometer with 70 - 85% efficiency. In June 2025, DARPA successfully transmitted 80 watts of power over 5.3 miles.

In 2020, the Naval Research Laboratories launched its space solar power experiment called PRAM, the Photovoltaic Radio-frequency Antenna Module. PRAM’s purpose has been to test the functional components of power satellite networks that could transmit energy from space to anywhere on Earth. PRAM is part of a comprehensive investigation into prospective terrestrial use of solar energy captured in space.

On May 17, 2021 PRAM was launched aboard the Air Force X-37B Orbital Test vehicle. PRAM reportedly performed well in orbit. Aboard the X-37B orbital test vehicle, it is the first in-orbital-flight test of a solar-to-RF “sandwich module.” Its 12-inch square test photovoltaic module has an additional layer to collect the more blue in the spectrum in space. As a result, the system captures more power per unit area in space.

In January of 2023, Caltech’s low-cost, space solar power prototype MAPLE was launched into orbit. MAPLE, short for Microwave Array for Power-transfer Low-orbit Experiment, demonstrated the ability to wirelessly transmit power in space and to beam detectable power to Earth for the first time. Its power was successfully transmitted from space to a rooftop at the Gordon and Betty Moore Laboratory of Engineering at Caltech’s campus in Pasadena, California on May 22, 2023.

The impetus for Caltech's space solar program has been to democratize access to energy, wherever it is needed, just like the internet has democratized information. The program has been supported by Donald Bren, Chairman of The Irvine Company and a lifelong Caltech board member, and his wife Brigitte Bren. They committed $100 million to Caltech's research. Caltech's work has also been supported by the Northrop Grumman Corporation in a space-based research agreement.

On December 5, 2025, Japan officially became the first nation in history to generate electricity in space and successfully transmit it back to Earth. Through its Ohisama project, the Japan Aerospace Exploration Agency (JAXA) beamed several kilowatts of microwave power from an orbiting solar array down to a receiving station on the ground, converting it into usable electricity with "remarkable efficiency." This marks the first time meaningful power has ever been wirelessly delivered from orbit to the Earth's surface, turning a concept first proposed in the 1960s into working reality.

Japan has now taken the lead in space solar power, a technology many experts believe could eventually supply a significant portion of humanity's future energy needs. The future of unlimited, always-on clean energy just moved from science fiction to proven engineering, and it happened first in Japan. According to JAXA, energy can now be wireless and limitless.

System Losses and Net Gains

Beaming power from space incurs system losses indeed. But the starting point is much greater than on Earth. Energy in space is 6 - 9 times as intensive as it is on Earth, and it is available 24*7. As such, losses are acceptable. What is key is the net system generation. The following simple summary is based on mid-point values for the losses listed.

System Component Losses	Net Efficiency
Power Conversion in Space: 20 - 30% loss	75%
Atmospheric Absorption: 10 - 15% loss	62.5%
Receiver Inefficiency: 30 - 50% loss	42.5%
Beam Targeting Errors: 5 - 10% loss	37.5%

The literature reports that beaming power from space to Earth has an overall efficiency of 20 - 40%. This includes collecting sunlight in space, converting it to electrons, then to RF power, transmitting it

to Earth, receiving it, converting it to electricity, and delivering it to a utility substation for consumption.

Safety Concerns

One of the concerns about space solar power and its transmission to Earth is the beams themselves and their radiative values. Electromagnetic fields (EMF), in this case radio frequencies, are ubiquitous. A colleague noted recently that if you want to avoid electromagnetic fields (EMF), you'd better be prepared to move into a cave.

Electromagnetic fields are all around us, and thankfully, most are safe, non-ionizing forms of radiation. That said, there will inevitably be public concern about beaming power from space and invisible electromagnetic radiation. There are real and perceived health risks associated with beaming power, especially where people live and work. There is a potential for RF radiation to heat biological tissue rapidly which can lead to tissue damage.

Some say, "It just feels unsettling" to beam power using invisible radio frequencies. Well-designed systems use frequencies that some experts claim are, "not the much of a health risk"… in the 2.45 - 5.8 GHz range like wifi. RF emissions from microwave ovens, tablets, and other portable devices that are operating below 6 GHz are regulated. These are non-ionizing forms of radiation that do not damage DNA like gamma rays and X rays.

The FCC has guidelines for safe exposure levels of RFs. Mobile phones are among the devices that have received the most scrutiny. Manufacturers have to post and adhere to Specific Absorption Rate (SAR) values for mobile phones. While mobile phones are considered safe, they can pose risks if in close proximity to implanted devices such as pacemakers. The FCC also regulates RF from wireless and PCS towers, and from amateur radio stations that are above 6 GHz. The guidelines specify power density, defined as the amount of RF power per unit area.

"Lasers and microwaves may conjure images of death rays and unanticipated health risks," stated an MIT Technology Review article in 2022, despite being deemed to be safe. It reports that the public is comfortable living amidst invisible forces like wi-fi and wireless data transfer, power beaming is simply the newest chapter. Some space solar power advocates encourage exclusion

zones to keep people and wildlife safely away from receiving stations and power beams. Imagine accidental exposure to intense radiation.

Environmental Considerations

The space industry is booming. Exponential improvements in technology since the first space race in the 1950s and 1960s means that more countries are participating and more rocket launches are occurring. Currently the impacts are nowhere near as great as the impact from aviation, but that may change if no mitigating action is taken.

Over the past 15 years, the number of rockets launched per year has nearly tripled, and the number of satellites orbiting the planet has increased tenfold, according to Statista. Climate One reports that the last few years have marked the start of the "second space race." Some forecast that ~100,000 spacecraft may circle Earth by the end of this decade. That will require a lot of launches. SpaceX plans to colonize Mars by 2050, launching three rockets per day to do so.

The increase in the frequency and intensity of space ventures poses significant environmental consequences. Impacts occur due to combustion of launch fuels, local area land impacts, and the impacts of space debris gasifying as wasted satellites deorbit and burn up. Advances like reusable rockets, cleaner fuels, and carbon-neutral initiatives offer hope for reducing environmental harm.

Launch Effects

Acoustic & Thermal Pollution

Rocket launches are extremely loud. The Saturn V rocket launch, for instance, created a 204 decibel (dB) roar. That's much louder than the sound of a jet airliner taking off, usually between 120 and 160 decibels. The Center for Disease Control states that sound levels 85 dB and above are potent enough to cause hearing loss.

Habitat and Wildlife Impacts

The uptick in rocket launches is also having a tangible impact on the planet's surface. At SpaceX's Boca Chica facility in Texas, a protected wetland for vulnerable species has suffered extensive damage. Launches from Starbase, Texas, are known to cause disturbances to local ecosystems, habitats, and protected bird species. Similarly, decades of liftoffs from Russia's long-time space base

in Kazakhstan have led to the absorption of dangerous carcinogens into the vulnerable steppe ecosystem, an ecoregion marked by grassland plains.

Forming Clouds and Impacting the Weather

Studies have revealed that the exhaust from rockets can form artificial cirrus clouds. These have been found to trap heat, sometimes affecting the local temperatures. Clouds were observed after famous launches including the SpaceX Falcon 9 and Space Shuttle.

Rocket launches can impact the weather, but usually, the effects are localized and short-term. For instance, a rocket launch can create thin, high-altitude artificial clouds made up of the emitted water vapor, carbon dioxide, and particulate matter.

Intense Heat and Seeding Rainfall

The intense heat and shockwaves generated by launching rockets are other concerns. The launches can disturb the lower atmosphere, affecting circulation in the immediate area. Rocket exhaust particles (such as aluminum oxides) have also been found to act as cloud condensation nuclei, which can lead to localized changes in rainfall patterns.

Impacts to the Atmospheric Column

Rockets inject air pollution into higher layers of the atmosphere. While aircraft emissions are contained within the troposphere (up to 12 miles above the Earth's surface), rockets emit their exhaust throughout their climb through the atmospheric column. This is "untested territory." Scientists believe that there is a need for more research. One expert notes that our understanding of the consequences of these emissions decreases the further you get from the surface of the Earth.

The higher a rocket travels in the atmosphere, the longer the particles will remain – as long as 100 - 200 years – and the more havoc they may create. Some say that this unchartered territory could soon result in a major environmental crisis. Given this danger, the non-profit Public Interest Research Group called upon the FCC, which awards licenses for satellites, to halt all "megaconstellation" satellite launches – such as Starlink satellites – until the environmental impacts are known. Currently satellites are exempt from the National Environmental Policy Act of 1986 which required projects to prepare environmental impact reports.

Ozone Layer Damage

Rockets are a major culprit in depleting the ozone layer. Some of the propellants used by rockets, particularly solid-fuel and hybrid rockets, release dangerous compounds like chlorine that wear out the ozone layer, exposing the Earth to hazardous UV light. Hydrochloric acid (HCL), for instance, is an emission from rockets that use solid aluminum fuel, ammonium perchlorate (NH_4ClO_4) oxidizer, and hydroxyl-terminated polybutadiene (HTPB) as propellant. The problem with HCL is that once it gets into the atmosphere, it breaks down to release chlorine atoms, which destroy the ozone molecules.

Launch Fuels and Emissions

Most rockets in use today run on fossil fuels and release soot which absorbs heat and thus increases temperatures in the upper levels of Earth's atmosphere. Some researchers are concerned about the effects of routine space travel on the Earth's atmosphere. A comprehensive study from the National Oceanic and Atmospheric Administration (NOAA) found that more spaceflight activity leads to more black carbon emissions directly into the stratosphere, with downstream consequences for the ozone layer.

Future Eco-Friendly Fuels

Some launch vehicles use liquid rocket propellants such as liquid hydrogen (LH_2) and liquid oxygen (LOx). Much like fuel cells, these rockets will only exhaust water vapor. But some experts claim that carbon-free rocket fuels "remain hypothetical for now" as they are costly. They note that science is many years away from pollution-free space travel.

Rocket Emissions

Rockets release CO_2, carbon black (soot) and other GHGs depending on the propellant used. Unlike aviation pollution, which is in the lower atmosphere and can be reabsorbed through natural processes, rocket emissions in the upper atmosphere can linger there for many years.

Carbon Dioxide

Each SpaceX Falcon 9 rocket launch emits 116 tons of CO_2 in the first 165 seconds, less than three minutes. And that's just the initial stage. These rockets use kerosene-based fuel and release a total of 200 - 300 metric tons of CO_2 per launch. Space X's Starship is the largest rocket ever built. This

5,000-ton rocket is designed to be one of the cleanest. Its raptor engines use liquid methane and liquid oxygen, which aren't as toxic as kerosene-based fuel. However, methane combustion emits CO2 and water vapor but without chlorine-based emissions that come with solid rockets. Starship's CO2 impact per launch is 1,000–1,500 metric tons, albeit less than NASA's Space Launch System whose emissions can be over 4,000 metric tons per launch.

Black Carbon

Black carbon, or soot, is worse than CO2 in that it contributes to global warming and also causes melting of snow and ice when deposited on their surfaces. Black carbon is emitted by rockets that run on kerosene and hybrid fuels. By one count, rocket launching accounts for 10% of all soot in the stratosphere. Soot is so potent at causing the warming effect that just 1,000 tons of it in the atmosphere is enough to warm Earth by 1 degree Celsius in some regions. The effect of these emissions is not clear, and budget cuts to NASA and NOAA have left academics and the private sector with knowledge gaps related to black carbon.

Rocket Fuels

Rocket Design

Multistage rockets are designed to efficiently reach space. These rockets have two or more stages each with its own engine(s) and propellant. When the fuel in the one stage is depleted, it is jettisoned and the next stage is ignited… allowing the rocket to continue its ascent.

Most orbital vehicles are two-stage, sometimes called tandem or serial stages. The first stage is known as the "booster stage." It provides the initial thrust. It is the largest stage and is located at the bottom.

Mounted on top is the "sustainer stage." It ignites after the booster's fuel is depleted, and propels rockets to higher altitudes and speeds. This stage has a lower thrust-to-weight ratio and is more fuel efficient. This process of "rocket staging" is essential to achieving orbit and escaping Earth's gravitational pull.

Types of Fuels

Solid rocket fuels are reliable and fuel efficient. They are considered reliable due to their simplicity. They also have high thrust-to-weight ratios. The Space Shuttle uses liquid hydrogen and liquid oxygen to power its main engines in orbit. Space X chose to use methane as a fuel. SpaceX launches use Falcon 9 rockets and an aviation propellant similar to kerosene.

Some rockets use fossil fuels that pollute like any other carbon-based fuel. In terms of pollution on Earth, the First Stages in rockets fire for ~ 2 minutes and are finished. Their pollutants fall back to Earth and for the most part have no long-term effects if any. At least three scientific research papers have already been published this year on the impact of rocket emissions on the atmosphere, temperatures, and the ozone layer. Some scientists are worried that these carbon particles can act like a form of geo-engineering by absorbing heat.

Many other rockets use liquid H2 / O2 in their upper stages, which is much more efficient than fossil fuels but is cryogenic and the resulting by-product is water. NASA rockets have H2/O2 upper stages. Bezos' Blue Origin upper stages use H2/O2 as well, as does almost everyone else.

For cost economy, SpaceX's rockets reportedly use fossil fuels exclusively because they are cheaper and simpler. Some Russian rocket upper stages use fossil fuels as well. At the high altitudes where those upper stages burn, the pollutants can stay in the atmosphere for a very long time. That is the real long-term pollution danger.

Starship has Raptor engines that burn liquid methane, which is the main component of natural gas, and liquid oxygen. Domes within the aircraft separate the methane and oxygen fuels; The engines burn subcooled propellant… cooled below their boiling points to further increase their density and engine mass flow rates.

Satellite Fuels

Satellites use fuels on board to operate and maneuver in space. Fuels are used to move in orbit, reboosting and avoiding collisions with space debris. They use monopropellants, bipropellants, and hypergolics. Hydrazine is the primary fuel for satellites. It is highly toxic and requires special handling.

Refueling in orbit is on the radar too. There is considerable research and development of refueling satellites through propellant-transfer technologies. There is the possibility of robotically refuelling in space though this is seen as extremely hard. SpaceX's Starship is planning on utilizing refueling in orbit… topping off the tanks to jettison to the Moon and Mars.

The Space Elevator

One of the most far-out notions for getting into space is to build an elevator to do so. Also referred to as a "space bridge," "star ladder," and "orbital lift," is a proposed type of planet-to-space transportation system often depicted in science fiction.

A space elevator would consist of a cable with one end attached to the surface near the equator and the other end attached to a counterweight in space beyond Geostationary Orbit. The competing forces of gravity, which is stronger at the lower end, and the upward centrifugal pseudo-force, which is stronger at the upper end, would result in the cable being held up, under tension, and stationary over a single position on Earth.

With the space elevator's tether deployed, climbers/crawlers could repeatedly climb up and down the tether by mechanical means, shuttling cargo to and from orbit. The design would permit vehicles to travel directly to orbit without the use of large rockets.

End-of-Life Issues

Space Debris

There are currently more than 9,300 tons of space objects, mostly in Low Earth Orbit. These are made up of inoperative satellites and chunks of spent rocket stages.

On December 9, 2025, the Shenzhou 20 spacecraft was deemed unfit to carry astronauts back to Earth after suffering a space junk strike.. A two-man, eight-hour spacewalk was used to inspect the spacecraft and its damage outside of the Tiangong space station.

Jettisoned Stages

Big rockets have several stages, each having its own engine and fuel. Once a rocket stage runs out of propellant, that stage detaches and is jettisoned from the rest of the rocket to lighten the load. Then the next stage drives the rocket until its fuel is exhausted before falling.

Jettisoning the early stages maximizes the rocket's efficiency by getting rid of the "junk weight." But the jettisoned stages often fall into oceans, sometimes releasing dangerous compounds into the water and disturbing seabed organisms. In some cases, the carnage from rocket explosions during tests, especially at the initial stages, can fall into the ocean, affecting marine ecology.

Reusable Design

The 100% reusable design of Space X's Starship means less space debris and waste from discarded rocket stages. That means fewer raw materials like aluminum, titanium, and composites will need to be mined, significantly reducing the environmental impact associated with traditional rocket production.

Atmospheric Incineration of Satellites

When satellites reach the end of their useful lives, they either fall from space and incinerate along the way… or are programmed to be pushed into the internationally recognized "debris orbit." In the former case, the atmospheric incineration of satellites produces aluminum oxides, which too can alter the planet's thermal balance and cause ozone depletion. A study published in the journal Geophysical Research Letters found that concentrations of aluminum oxides in the mesosphere and stratosphere could increase by 650% in the coming decades due to the rise in reentering space junk.

Other researchers have suggested that the shroud of metallic ash that is forming in the stratosphere as a result of the satellite reentries may interfere with Earth's magnetic field. The satellite dust could weaken the magnetic field, the researchers think, possibly allowing more harmful cosmic radiation to reach the planet's surface.

To take on the growing issue of space debris, NASA and the Japanese have launched the first wooden satellite into space, made of magnolia wood after testing three kinds of wood: cherry, birch, and magnolia. LignoSat is an attempt to make space junk biodegradable. It is a coffee mug-sized satellite and was successfully deployed from the International Space Station in 2024. The goal is to make spaceflight more sustainable: Wood does not burn or rot in the lifeless vacuum of space and will incinerate into a fine ash upon reentry.

Number of Satellites in Space

SpaceX now has over 8,600 Starlink satellites in space formed in what are called megaconstellations. This number is expected to grow to 40,000. Each Starlink satellite is replaced every five years making room for newer models. As a result, a satellite is plunging to Earth every day; sometimes multiple satellites per day. The spent and hurtling satellites fall toward Earth and tend to burn up in the atmosphere, 37 - 50 miles in space.

Debris vaporizing in the atmosphere forms pollution that will remain there for decades, potentially damaging the ozone layer and impacting the Earth's albedo, its ability to reflect sunlight. Some 1,100 pounds of incinerated satellite trash each day, most satellites are made of aluminum which turns into aluminum oxide when burned at high temperatures, notably those experienced by satellites hurtling through the Earth's atmosphere at orbital speeds. Some say that aluminum ash could be the next environmental emergency.

Rocket launches are one thing, with jettisoned stages raining down from on high, the rise of megaconstellations of satellites with short lifespans is another great concern. These constellations are creating tons of space junk. According to Smithsonian Astrophysicist, Jonathan McDowell, there are more than one or two of Starlink satellites falling back to Earth every single day… and that number is going to keep climbing.

Megaconstellations

The population of Starlink satellites in Low Earth Orbit is rapidly rising due to expendable satellites. There have been thousands launched by Starlink since 2019 with more than 8,600 currently in operation. So far, Starlink has launched more than 2,000 in 2025 alone.

Amazon's Project Kuiper aims to provide fast, reliable broadband internet globally through a constellation of 3,236 Low Earth Orbit satellites. As of September 2025, Project Kuiper had launched 129 satellites into orbit. Its most recent launch was on September 25, 2025 when it launched 27 satellites. These were deployed by United Launch Alliance (ULA) using an Atlas V rocket. Amazon has committed to launching >80 missions to establish its satellite network. Experts anticipate about 30,000 low earth orbit satellites thanks to Starlink, Amazon's Project Kuiper, and others. Additionally, there may be another 20,000 Chinese satellites at a higher elevation, 620 miles into space.

Starlink satellites have a short lifespan of about five years. At the end of their lives, they are guided towards Earth where they're supposed to burn up upon re-entering the atmosphere. Given their sheer numbers, some astronomers have concerns about the ozone layer and the pollution caused by releasing materials in the stratosphere. These satellites could cause a chain reaction damaging the ozone layer, although some experts claim "no problem."

The Federal Aviation Administration reported in 2023 that there may be on the order of 28,000 fragments from Starlink satellites that could survive re-entry each year. This may "skyrocket" the chances of someone on the ground getting struck and killed by space debris. Experts believe that the chance of getting hit has gone from an astronomical improbability to a staggering 61% chance each year. Some experts postulate that there could be five satellite re-entries per day in the near future.

Satellite Collisions

Fuels are needed to stay in orbit. A portion of the fuel on any given satellite is reserved for changing orbits, avoiding collisions and debris. When nearly out of fuel the satellite must be removed. The only publicized satellite collision occurred in February 2009 between an American Iridium 33 satellite and a defunct Russian Satellite Kosmos 2251. The collision generated thousands of pieces of space debris. Experts warn of a worst-case scenario in which a disastrous chain reaction, known as the Kessler Syndrome, occurs starting with a few collisions that cascade out of control and beget more space debris, potentially trapping humankind below a whirling vortex of orbital shrapnel.

NASA and the European Space Agency actively monitor satellite positions and perform maneuvers to avoid collisions. Megaconstellations proliferation of satellites will lead to orbital overcrowding, increasing the likelihood of collisions and creation of additional debris. Ongoing dialogues between space agencies, private companies, and governments will be essential. As of the end of March 2025, there were 14,904 satellites in space. They are regulated by the United Nations Office for Outer Space Affairs (UNOOSA).

Conclusion

In recent years, improvements in satellites, radio frequency transmission, and the need for sustainable energy solutions have catalyzed the concept of space solar power. Beaming power from space began as sci-fi and has now matured.

Many organizations in many countries are exploring space solar power. Now testing has begun to prove its efficacy for power collection and transmission. Given the vast global thirst for clean power coupled with the speed of innovation, there is little doubt that space solar power will be tapped. Many companies and organizations are rapidly advancing this technology.

The space race is accelerating, ushering in space solar power, and bringing both innovation and environmental challenges. Rocket launches contribute to carbon emissions, ozone depletion, and space debris, raising concerns about long-term sustainability. Myriad Earthly environmental concerns related to the space race that must be addressed. While space travel is essential for scientific progress, harvesting power, and future colonization, its impact on Earth cannot be overlooked.