74th International Astronautical Congress (IAC 2023), Baku, Azerbaijan, 2-6 October 2023.

IAC-23-C3.1.12

Space Solar Power - 2023 Survey of Public and Private Initiatives

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Abstract

The urgency and relevance of exploring new green energy sources has never been greater. In addition to the de-carbonization challenge, recent geopolitical crises created a turmoil in energy markets, leading to an increase in prices. Space-Based Solar Power (SBSP), and Space Solar Power (SSP) for shorter, has been proposed as an alternative energy source to address these challenges. By providing a virtually limitless source of clean energy and with the ability to reach remote areas around the world that currently lack good access to electricity, SBSP has the potential to transform the energy sector and have a wide positive impact.

The concept of space solar power has gained significant momentum in recent years, with various trends converging to make large-scale solar power plants more realistic and economically viable. Factors such as Starship, in-space assembly, power beaming, and other performed and upcoming demonstrations in space coupled with key technological demonstrations on the ground, have all contributed.

The first part of the manuscript examines enabling trends and technologies, including efficient solar panels, low-cost reusable launch, advanced wireless power transmission, in-space robotics and assembly, and distribution capabilities. Focusing on what has been done and what needs to happen for SBSP to be developed and with the right timing. This section will explain why the time for SBSP is looming and how research and development in this field may have additional beneficial applications, particularly if the economic sustainability is not achievable within the predicted time frames.

The second part of the paper presents an overview of commercial entities that were, are or intend to be active in the SBSP market. A combined table and a paragraph for each surveyed SBSP entity is included. The findings include past companies and present-day startups. This data will entail information such as founding years, planned space demonstrations, funding amount, and geographic locations.

The third part looks at non-commercial initiatives, such as those by ESA, UK, NASA, Japan, and China, and gives a short overview to understand the actors and state of technology development. This paper aims to present a comprehensive and unique analysis of the space solar power landscape.

Keywords: space solar power, space-based solar power, power beaming, SBSP, SSP, space energy

1. INTRODUCTION

Factories in Space (www.factoriesinspace.com) has tracked space solar power and wireless power transfer companies since 2018. There are 52 primarily commercial entries as of September 2023, which makes it one of the largest public lists.

Goal of this work is to leave a snapshot of the space solar power landscape such that the field can be tracked over the upcoming years. Focus is on surveying the past and present commercial entities in addition to governmental and other activities.

Numerous publications, books, and articles in the last decades have covered the history, benefits, literature reviews, technical concepts, challenges, and recent news, for space solar power.[1–3] For example, many of those aspects have recently been recounted in study papers commissioned by the European Space Agency (ESA), such as the cost vs benefit studies[4] and Astrostrom 2023 study.[5]

However, broad contemporary surveys about commercial activities in space solar power have not been found. Closest known is SpaceFund's Energy Transmission Database, which was last updated in August 2021 and has 10 entries.[6]

National Space Foundation has been collecting links to space solar power and it is very extensive.[7]

This survey includes activities from space solar power, power beaming (wireless power transfer) and solar mirrors (reflecting sunlight directly). However, there must be a space and energy connection and the solutions must involve wireless energy. The latter are also core technologies of many space solar power systems, and organisations may choose to start the research and development from wireless power.

Space Solar Power In 1968, Peter Glaser published the first engineering concept of space solar power to provide energy for terrestrial use.[8]

In the original concept, space-based solar power involved collecting sunlight in orbit, converting it to electricity, sending the energy wirelessly to Earth, where a rectenna on land or offshore would convert it back to electricity, which would be connected to the electric grid or consumers.

In this survey, the range of solutions and applications is wider, but there must be a space connection and an element of wireless energy transfer. For example, solar panels on the Moon, wired to the consumer, is not space solar power in this survey. It is lunar solar power, space energy and a space utility, but here space solar power assumes some type of power beaming to align with the original concept.

In the Factories in Space taxonomy for in-space economy,[9] there is a high-level category of Space Utilities, under which is Space Energy (energy resources in space[10]), and Space Solar Power is a type of energy in space. Space Solar Power (SSP) is a shorter term for Space-Based Solar Power (SBSP). The spacecraft have been called Space Solar Power Satellite (SSPS) or Solar Power Satellite (SPS). Descriptively, space energy, energy from space, energy on the Moon etc have also been used.

Table 1 is a non-exhaustive overview of the different space solar power solution configurations. For example, some SSP systems have very large solar arrays, while others use concentrating mirrors with smaller solar arrays. Wireless power transfer can be achieved via microwaves, laser or by reflecting sunlight directly. In addition to Earth, the power may be beamed to assets in space or on the Moon. A wireless energy grid may involve beaming power from Earth to space and then back to Earth. The spacecraft may also be located in different orbits, such as LEO, Molniya or GEO.

Table 1: Space Solar Power Configuration Options

Power generation	Solar arrays
	Mirrors plus solar arrays
Power beaming	Microwaves (e.g. 2.4-10 GHz)
	Lasers (optical)
	Solar mirrors (direct sunlight)
Paths	Space-to-Earth
	Space-to-Moon
	Space-to-space
	Lunar surface-to-surface
	Earth-space-Earth
	Moon-to-Earth
Locations	GEO
	MEO
	HEO, Molniya
	LEO
	Lunar orbit
	Lunar surface
	Lagrange points
Earth receivers	Land
	Offshore
	Air

Power Beaming Power beaming or wireless power transfer (WPT) or wireless power transmission or more broadly wireless energy transfer, in the context of space, has been included also. Being one of the core technologies with alternative applications for shorter-term revenue, many companies have chosen that as the starting point towards space solar power. As solar mirrors (reflecting sunlight directly) are also included, power beaming could be defined as transmission of concentrated energy without wires.

Transmission of electrical energy without wires was observed and experimented with in the 19th century. There was limited progress until microwave technologies were improved during World War II. The rectenna (a receiving antenna, which converts microwaves to electricity) concept was proposed for wireless power transfer by W. C. Brown at Raytheon in the 1960s. The first microwave rectenna was built by R. H. George at Purdue University in 1963. In 1964, Brown built a helicopter with an array of rectennas and demonstrated flight on CBS News in 1964.[11] First functioning laser was operated in 1960.

The idea of using mirrors in space like giant spotlights was proposed in 1929 by Hermann Oberth. It has been tested by Russia during Znamya experiments.[12] These large solar mirrors are beginning to relate to solar geoengineering and the concept of using giant mirrors in space to shield Earth.[13]

Commercial space solar power entities have been collected in Table 2 followed by short descriptions of them in Section 4. Statistical overview of the 52 commercial entities can be found in Section 5. Section 6 introduces the non-commercial and governmental organisations in the space solar power field.

Acronyms/Abbreviations
SBSP Space-Based Solar Power
SSP Space Solar Power
SPS Solar Power Satellite
SSPS Space Solar Power Station
WPT Wireless Power Transmission
GEO Geostationary Orbit

2. ENABLING TRENDS & TECHNOLOGIES

2.1 Why Now? Trends Are Converging

Most studies since the 1970s have concluded that space solar power is technically feasible but not economically viable. In 2023, new energy crisis and climate crisis have contributed to the renewed interest. At the same time, the key limiting factors such as low-cost reusable launch are being rapidly solved. High electricity prices and decreasing cost to build space solar power plants means that the trends are starting to converge, to make space solar power also economically feasible, for the first time in history.

2.1.1 Energy Crisis, Climate Change

During the 1973 oil crisis, the prices increased about 4 times.[14] The energy shortages of 1973 created interest in the space solar power concept and in 1976, the Department of Energy and NASA initiated an SPS Concept Development and Evaluation Program.[15] In 1979, the fossil fuel prices further increased over 2 times but afterwards declined and stayed relatively low for about 30 years.[14]

A new energy crisis in 2021-2023[16] has increased the energy prices and CO2 levels keep rising, thus the need for clean energy sources is highest ever.

Terrestrial solar and wind are intermittent. Due to the limited capacity and intermittency, they are being augmented by coal, oil and gas. Nuclear energy has to contend also with emotional factors. A space solar power station in GEO can be in sunlight and operate 24/7 continuously for almost the whole year. This enables space solar to be a true replacement for coal, oil, gas and nuclear, while solar and wind will require large energy storage to do so.

2.1.2 Launch

Access to space has two critical factors, price per kilogram and mass to orbit within a time frame. SpaceX's Starship is aiming to solve both.

Starship is being designed for 3 flights per day and be fully reusable. One rocket could theoretically fly 1000 times per year. More, the goal is to build hundreds if not thousands of Starships. With each launch having a payload of about 100-150 tons, the mass to orbit per year can increase enormously.

In terms of cost, the goal is to decrease cost per Starship to below $10 million in a few years. Longer-term, it could even cost a few million dollars in the future.[17] Assuming $10M and 100,000 kg equals $100 per kilogram. In the most optimistic case, assuming $3M and 150,000 kg gives $20 per kg.

2.1.3 Solar Cells

The cost, production capacity, and lifetime of solar cells has been considered another limiting factor.

A triple-junction gallium arsenide (GaAs) solar cell price is on the order of $100 per watt. Assuming 1 GW of power generation capacity, and a system with no concentrating mirrors, the price of solar cells itself would amount to $100 billion. Such quantity is also beyond the worldwide production capability.

In 2023, several solutions and new types of solar cells are close to market readiness. One is a thin-film low-cost silicon solar cell, for example developed by Solestial. Their thinness helps to decrease mass and volume. Self-curing is very beneficial to extend lifetime.[18] In longer-term and at large quantities, prices below $1 per watt have been quoted.[19] Silicon solar cells are widely used in terrestrial solar farms thus production capacity solutions are known.

The current efficiency of silicon cells is less than for multi-junction, about 20%, but some architectures for the large-scale space solar power plants should be able to negate that thanks to microgravity.

Perovskite solar cells could be printed.

2.1.4 Power Beaming (Wireless Power Transfer)

Very simplistically, telecommunications and TV broadcasting spacecraft in GEO have done power beaming since the 1960s using similar S-band or C-band frequencies. Differences are that the output power would be much larger, no data would be sent, and the antenna will be much larger to ensure small divergence of the beam.

Electronically steerable phased arrays been used for decades in military applications, but the cost has now decreased enough to find commercial applications like Starlink Dish. They enable e.g. to use a near-field system, which Emrod has described.[20]

2.1.5 In-Space Assembly, In-Space Robotics

The best known examples for assembly in space are the Mir and International Space Station.

Kilometer-scale space solar power plants have been compared to the football-field size of the ISS. However, such large size is an engineering problem, to build it autonomously and rapidly at low cost, and not a fundamental scientific problem.

As of 2023, several new in-space assembly and in-space manufacturing demonstration missions are in development. For example, the OSAM-1 mission is planned to launch in 2025. Its SPIDER payload will assemble 7 elements using a robotic arm to form a 3 meter diameter communications antenna.[21]

2.2 Alternative Technology Applications & Revenue Sources

The are many alternative benefits, nearer-term revenue sources, and separate potentially very large markets for the technologies related to space solar power. While discussing that the research and development funding will not be a waste, in this section the author is assuming that the economic viability of space solar power for terrestrial purposes takes considerably longer or even never happens.

The following examples are non-exhaustive.

2.2.1 Moon

The clearest application and need for small-scale space solar power and wireless power is likely on the surface on the Moon, to survive the 2-week long lunar nights or to explore permanently shadowed craters. Surviving the lunar night is very challenging and existing reliable systems have used nuclear heating. First solutions will likely use monolithic spacecraft and laser power transmission, due to smaller beam divergence to maximize the small surface area available on a lander or rover. However, the solar cells for laser will likely have to be single-junction. Two different solar panels may thus be required, which requires customers to plan for such a service far in advance, which they may be hesitant to do.

2.2.2 Space

Wirelessly powering other satellites is a business idea many startups have had. More power can be beneficial or the eclipse period could be shortened, assuming the spacecraft is able to dissipate the heat. However, the business case will likely require more in-depth studies. It is possible that it will be better, in terms of lower cost, independence and practicality, to simply have larger solar panels and batteries.

2.2.3 Mars

Space solar power with microwave power transfer could be a viable energy source on Mars. Microwaves are less affected by dust compared to sunlight, both in the atmosphere during dust storms and for dust accumulation on the Mars surface. The cost difference between access to Mars orbit and Mars surface may become an important factor.

2.2.4 In-Space Assembly

In-space assembly can have many applications in fields such as Earth observation, an existing market.

The author is envisioning over 1 km diameter space telescopes for astronomy. Similar extremely large space telescopes could be used for ultra-high resolution persistent remote sensing, e.g. from GEO and highly elliptical orbits.

Extremely large antennas could also be built for usage in radar remote sensing, telecommunications, radio astronomy and deep space communications.

Going beyond existing markets, in-space assembly will enable to construct very large artificial gravity space habitats and other infrastructure.

2.2.5 Wireless Power Transfer

Numerous companies are pursuing terrestrial applications for large-scale wireless energy transfer. Including a wireless energy grid, part of which may be based in space. Remotely powering electric airplanes should make them easier with existing batteries.

2.2.6 Space Debris Removal

NASA study found that space-based laser debris removal systems have the shortest break-even time, compared to other potential methods.[22]

2.2.7 Beam-Powered Propulsion

There are many variations for beam-powered propulsion. For example, a very large laser array in space would allow laser sailing to interstellar destinations. In our solar system, power beaming stations could be placed in several key locations to enable very efficient travel between planets.

Figure 1: Space Solar Power Station Illustration Generated by the Author Using Midjourney

3. SURVEY APPROACH

This section describes the survey methodology, which has resulted in the 52 entries and provides explanation about the classifications used to categorize the space solar power organisations.

The entries have been collected over 5 years while curating the Factories in Space database. Because similar large and structured sources have not been found, the discovery is the most challenging part.

It is likely that many suitable entries are missing, especially some older and now defunct ones, and more importantly the recently emerging entities.

Survey Criteria

- Space solar power, power beaming and solar mirror activities included.
- Must have a clear space & energy connection. There is a large amount of terrestrial activities in power beaming and solar mirrors but there has to be a space and energy aspect or goals.
- Must involve some type of energy beaming. Solar farms on the surface of the Moon using wired connections have not been included.
- Based on public information - websites, articles, publications, social media posts etc.
- Interviews have not been performed this time.
- Technical solutions have not been surveyed and compared, but many space solar power concepts are nevertheless referenced.

Status Classification

One of the following statuses has been assigned to each space solar power activity, based on public information, and in some cases by the lack of it.

- **Operational** - Space solar power spacecraft are in space, or on the Moon, and providing energy to customers using power beaming.
- **Demonstrated** - Core technologies of space solar power have been demonstrated in space, and/or full end-to-end demonstration missions have been launched.
- **Development** - Suitable indicators are two or more of: the company and project is visibly active, hardware development, terrestrial prototypes, the year for the first launch has been announced, relevant updates on social media channels and news, team size is increasing, private funding has been announced and/or governmental projects awarded.
- **Concept** - Alternatively, idea or study stage. Possible indicators are: one-off study project and hardware development has not yet begun, awarded study grants, lack of proof about sustained technical development, active development is unlikely based on funding level, types of updates on social media and via news media, team very small based on LinkedIn. In other words, performing a study or creating a website does not equal a new space solar power company in the development stage. In addition, due to the nature of some entities, they may not intend to develop own space solar power plants. This status may be the most debatable, and some may be in stealth mode, but active development may still start.
- **Early stage** - Startups, with a clear intention to develop space solar power, but which have a very small team and possibly limited or no funding. Mostly applies to the recent emerging entities, of which little is publicly known, but it also includes companies that have been around for years but seemingly limited progress.
- **Dormant** - The first step towards Cancelled. Possible indicators are offline website, lack of recent posts on all social media channels, very small team or a single person based on LinkedIn, and/or no announced funding.
- **Cancelled** - Indicates a space solar power project, which has been announced to have been stopped, or which website has been offline for years, or no indication of space solar power on the organization website when it used to be before, or company officially bankrupt and closed.

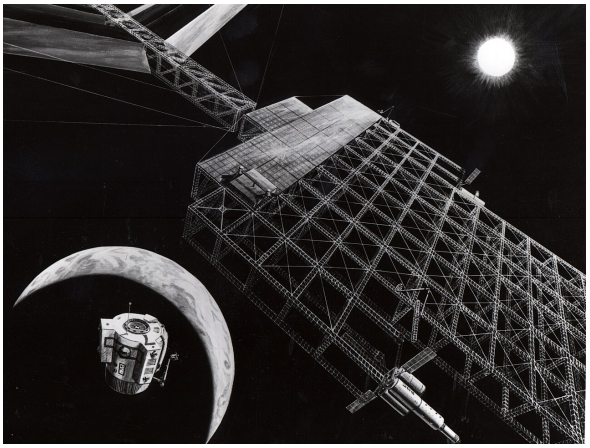

Figure 2: NASA Solar Power Satellite Concept, 1976

4. COMMERCIAL LANDSCAPE OF SPACE SOLAR POWER

Table 2 collects the 52 surveyed commercial entities in the space solar power field. It is followed by short descriptions of the organisations.

Table 2: Space Solar Power Commercial Activities

Organisation	Status	Founded	First launch	Funding	Category	Target	Location, Orbit	Path	Beaming	Power generation	Country
3K SpaceTech	Early stage	2021	?	?	Power Beaming	Space	?	Space-to-space	?	?	Canada
Airbus	Concept	1970	?	Yes, ?	Space Solar Power	Earth	?	Space-to-Earth	Microwave	?	France
Alvior	Early stage	2022	?	?	Space Solar Power	?	?	Space-to-Earth	?	?	Norway
Aphelia Space	Early stage	2022	?	?	Power Beaming	Space	LEO,?	Space-to-space	Microwave	?	Malaysia
Aquila Earth	Development	2022	?	$2.1M+	Power Beaming	Earth	?	Earth-space-Earth	Laser	Mirrors	Australia
ARTEMIS Innovation	Concept	2005	?	?	Space Solar Power	Earth	GEO	Space-to-Earth	Microwave	Mirrors plus solar arrays	USA
Arthur D. Little	Concept	1886	?	Yes, ?	Space Solar Power	?	?	Space-to-Earth	?	?	USA, UK
Astrostrom	Development	1998	?	$0.3M+	Space Solar Power	Moon, Earth	Lagrange, GEO	Space-to-Moon, Space-to-Earth	Microwave	Solar arrays	Switzerland
Celestia Energy	Early stage	2023	?	?	Space Solar Power	Earth	?	Space-to-Earth	Laser	?	United Arab Emirates
Emrod	Development	2019	2025	$3.3M+	Power Beaming, Wireless Energy Grid	Earth	LEO, VLEO	Earth-space-Earth	Microwave	?	New Zealand, Germany
EnergySpace Company	Dormant	2020	X	?	Power Beaming	?	?	?	?	?	USA
Entropy	Dormant	2017	X	?	Power Beaming	Space	?	Space-to-space	?	Solar arrays	India
Eternal Light	Development	2020	?	$0.1M+	Power Beaming	Moon	Lunar orbit	Space-to-Moon	?	?	Canada, USA
Frazer-Nash	Concept	1971	?	Yes, ?	Space Solar Power	?	?	?	?	?	UK, Australia
International Electric Company	Concept	1999	?	?	Space Solar Power	Earth	GEO	Space-to-Earth	Microwave	Mirrors plus solar arrays	UK

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Table 2: Space Solar Power Commercial Activities (Continued)

Light Mirror	Early stage	2019	?	?	Solar Mirrors	Space, Earth	?	Space-to-space	Sunlight	N/A	Lithuania
Litepulse	Early stage	2022	?	?	Power Beaming	Space	?	Space-to-space	?	?	USA
Lumi Space	Cancelled	2018	N/A	$0.1M+	Power Beaming	Space, Satellite	Earth	Earth-to-space	Laser	N/A	UK
Metasat UK	Development	2020	?	?	Space Solar Power	Earth	?	Space-to-Earth	Microwave	?	UK, Canada
Moliri Space Energy	Early stage	2023	?	?	Space Solar Power	Earth	GEO	Space-to-Earth	Microwave	Solar arrays	Estonia
Northrop Grumman	Development	1994	2025	Yes, ?	Space Solar Power	Earth	?	Space-to-Earth	Microwave	?	USA
OHB	Concept	1958	?	Yes, ?	Space Solar Power	Earth, Aircraft	?	Space-to-Earth	Laser	?	Germany
Orbital Power	Dormant	2011	?	?	Space Solar Power	Earth	?	Space-to-Earth	Microwave	Solar arrays, Inflatable	UK, USA
Overview Energy	Development	2022	?	$6.8M+	Space Solar Power	?	?	?	?	?	USA
ParaLoon	Development	2022	?	$0.05M+	Space Solar Power	Earth, Space	?	Space-to-Earth, Space-to-space	Microwave	Solar arrays, Inflatable	Belgium, Italy
Photonicity	Early stage	2019	?	?	Power Beaming	Space, Earth	?	Space-to-space	Microwave	?	Singapore
PowerLight	Development	2007	?	$4.1M	Power Beaming	?	?	?	Laser	?	USA
PowerSat	Early stage	2001	?	?	Space Solar Power	Earth	GEO	Space-to-Earth	Microwave	Solar arrays, Inflatable	USA
ReBeam	Dormant	2016	X	?	Power Beaming, Wireless Energy Grid	Space	?	?	?	?	USA, India
Reflect Orbital	Early stage	2021	2024	?	Solar Mirrors	Earth	?	?	Sunlight	N/A	USA
Roland Berger	Concept	1967	?	Yes, ?	Space Solar Power	?	?	?	?	?	Germany
Satellite Applications Catapult	Development	2012	?	Yes, ?	Space Solar Power	?	?	?	?	?	UK
Shimizu	Concept	1804	2035	Yes, ?	Space Solar Power	Earth	Moon surface	Moon-to-Earth	Microwave	Solar arrays	Japan

Continued on next page

Table 2: Space Solar Power Commercial Activities (Continued)

Sirin Orbital Systems	Early stage	2019	?	?	Power Beaming	Moon	Moon surface	Moon surface	Microwave	?	Switzerland
Solar Space Technologies	Early stage	2019	2027	?	Space Solar Power	Earth	?	Space-to-Earth	Microwave	Mirrors plus solar arrays	Australia
Solar System Resources	Early stage	2020	?	?	Space Solar Power	?	?	?	?	?	Poland
Solar.Space	Dormant	2018	X	?	Power Beaming	Space	?	Space-to-space	?	?	UK
Solaren	Development	2006	?	$2.5M+	Space Solar Power	Earth	?	Space-to-Earth	Microwave	?	USA
Solestial	Concept	2015	2024	$12.3M+	Solar Cells	?	?	?	?	?	USA
Space Applications Services	Concept	1987	?	Yes, ?	Space Solar Power	?	?	?	?	?	Belgium
Space Energy	Dormant	2008	X	$4M+	Space Solar Power	?	?	?	?	?	Switzerland
Space Power	Development	2019	2024	$0.01M+	Power Beaming	Space	?	Space-to-space	Laser	?	UK
Space Solar	Development	2022	?	$4.3M+	Space Solar Power	Earth	GEO	Space-to-Earth	Microwave	Mirrors plus solar arrays	UK
Spacefaring Services	Dormant	2014	X	?	Power Beaming	Space	?	Space-to-space	?	?	USA
Spacians	Dormant	2019	X	?	Space Solar Power	Earth, Aircraft	?	Space-to-Earth	Microwave	?	India, Sweden
Stellarion Energy	Dormant	2020	X	?	Space Solar Power	?	?	?	?	?	India
STELLS	Development	2021	2024	$0.5M	Power Beaming	Moon	Moon surface	Moon surface	Microwave	Solar arrays	Canada
SunCubes	Development	2021	?	?	Power Beaming	Space	?	Space-to-space	?	?	Italy
Thales Alenia	Concept	2007	?	Yes, ?	Space Solar Power	Earth	?	Space-to-Earth	?	?	Italy, France
The Lunar Grid	Early stage	2021	?	$0.15M+	Space Solar Power	Moon	Lunar	Space-to-Moon	Laser	?	Luxembourg
Virtus Solis	Development	2018	?	$0.4M+	Space Solar Power Power Beaming	Earth	HEO, Molniya	Space-to-Earth	Microwave	Solar arrays	USA, UK
XISP	Early stage	2012	?	?	Power Beaming	Space	?	Space-to-space	?	?	USA

4.1 3K SpaceTech

Founded in Canada in 2021, they strive to create a network of power supply stations throughout the solar system, as well as provide the ability to obtain energy on any satellite or planet.[23] In 2022, they announced cooperation with Plus Ultra Space Outposts to provide power to Moon-orbiting stations and surface stations that provide navigation and communication services for lunar missions. Later, they announced that first step would be to use their X-Charge station as data centers.[24] However, the website is offline, two employees on LinkedIn, and last social media post was over a year ago.

4.2 Airbus

In 2010, as Astrium, it was seeking partners to help fund solar-power beaming demonstration. After spending several months on in-house review and a small ground demonstration, they started seeking the interest of European governments for support for a large satellite in geostationary orbit. Applications foreseen were providing continuous power from space to ships at sea or other fixed or mobile users. Astrium steered clear of using microwave signals because of public concerns about health effects and because an infrared signal could provide 1 to 2 kilowatts per square meter of power and still be well within safety limits.[25,26]

Now, Airbus says beaming solar power could help Europe access more renewable energies, in an independent way, and has created several marketing materials. Airbus has demonstrated how this new technological concept could work in its X-Works Innovation Factory.[27] Emrod partnered with Airbus and the European Space Agency (ESA) for a wireless power transmission demonstration event in Munich, Germany, in September 2022.[28]

Airbus Ventures invested in Solestial, which is developing flexible solar cells and solar blankets, another core building block for SSP.[29]

4.3 Alvior

Alvior is a startup founded in Norway in late 2022 dedicated to accelerating the development of Orbital Solar satellites.[30] However, based on Twitter/X, the founder Kim Borgen seems to have switched focus to other ventures.[31]

4.4 Aphelia Space

Aphelia is a wireless power startup from Malaysia founded in 2022. They aim to make interplanetary smallsat space missions more economical while having higher capabilities. Their core technology is the Microwave Wireless Power Transmission System.[32]

Aphelia is building wireless charging station, that delivers kW-level of electrictricity to dedicated satellite constellations. Aphelia's Wireless Charging Station will navigate to the customer's satellites and deliver high power periodically until the final power to de-orbit for decommissioning of the satellites.[33]

4.5 Aquila Earth

Aquila, founded in 2022 in Australia, is building energy networks of light. In June 2023, they announced raising of ∼$2.1M ($3M AUD).[34] Plan is to direct light beams at receivers integrated into power systems, which convert energy into electricity.[35]

Aquila is build and operate a dynamic, light-based energy network that can extend and improve the capabilities of our energy distribution infrastructure. By beaming energy with lighthouse modules, redirecting it with mirrors, and capturing it with specialised solar panels, they can rapidly create transmission pathways and shift renewable energy worldwide, accelerating their uptake. Their long-term vision is a globe-spanning energy network consisting of thousands of optical relay satellites directing gigawatts of power worldwide.[34]

Currently, they are focusing on creating light-based energy products to serve small drone operators to supply power continuously to drones in-flight.[34]

Aquila published a whitepaper titled "Global Energy Interconnection" in July 2022.[36] Tom McLeod from Startmate published their investment notes on Aquila in September 2022.[37]

4.6 ARTEMIS Innovation

Artemis Innovation Management Solutions was formed in 2005 by John C. Mankins. They provide strong experience and expertise in the general area of space systems and technology, and unique capabilities in the field of space solar power (solar energy from space or solar power satellites).[38]

In 2011, Artemis Innovation was selected for a NASA NIAC Project for 2011 - "SPS-ALPHA (Solar Power Satellite via Arbitrarily Large Phased Array) - the First Practical Solar Power Satellite Concept." Also in 2011, The First International Assessment of Space Solar Power was published by the International Academy of Astronautics (IAA). Artemis Innovation played a lead role in that multi-year study (2008-2011).[38]

In 2014, John Mankins published a book "The Case for Space Solar Power".[39]

4.7 Arthur D. Little

Arthur D. Little is an international management consulting firm originally headquartered in the United States and founded in 1886.[40]

In November 1968, Peter Glaser, working at Arthur D. Little, proposed the concept of a space solar power to provide energy for terrestrial use.[8]

In April 2023, ESA awarded study contracts to develop new reference-design space solar power architectures for large-scale terrestrial use to Arthur D. Little and Thales Alenia Space Italy.[41]

However, it is currently unclear what kind of commercial interests they have and whether they plan to lead the development and building of space solar power plants.

4.8 Astrostrom

Astrostrom is based in Switzerland and the primary purpose is to introduce, promote and expand an economic, technological and cultural dimension to the astronautical endeavors of mankind, with a focus on the harvesting of energy from space.[42]

In July 2023, Astrostrom completed their ESA-funded study investigating the feasibility of a "Greater Earth Lunar Power Station (GEO-LPS)", which would manufactured on the Moon and assembled at the Earth-Moon Lagrange Point 1 to provide power from lunar orbit to operations on the surface of the Moon.[43]

4.9 Celestia Energy

A UAE-based startup founded in 2023 and focusing on the commercialization of Laser Space-based Solar Power. Goal is to design, develop, and manufacture satellites, which will be launched into orbit, where they will collect solar energy, and beam this energy down to Earth in the form of lasers.[44]

4.10 Electric Sky

Electric Sky was founded in 2014 in the USA and is pioneering movement under external power, making transportation more swift, sustainable & economical.[45] In December 2021, DARPA awarded $225,000 to develop technology to wirelessly charge drones mid-flight and they will build and test a lab-bench demonstrator at short distances. With their "Whisper Beam" technology, radio waves self-focus at the receiver, enabling the UAV to draw kilowatts of power in all weather. The waves are weak everywhere else, even directly between transmitter and UAV.[46,47]

4.11 Emerald Telecommunications

Emerald Telecom is a UK-based business telecoms supplier founded in 2019. They were awarded an ESA-funded study "SPS Station Keeping Using Solar Radiation Pressure for Propulsion" to investigate station keeping of solar power satellite using solar radiation pressure.[48]

4.12 Emrod

Emrod was founded in 2019 in New Zealand with the vision to open up the world's access to power by using power beaming technology to enable long range wireless energy transfer that is safe, reliable and cost effective.[49]

Emrod is proposing a global Wireless Energy Matrix (WEM), which would beam renewable energy via satellite between any two points on Earth. In an article by Loz Blain at New Atlas from 2022, Emrod was looking at another proposal that would place satellites in much lower orbits closer to 100 km – those would only need to be 30-40 m across, and thus much cheaper to build and launch.[20,50]

Emrod's WEM system deploys highly efficient wireless power transmission technology to establish a global energy grid. Terrestrial transmitters and receivers collaborate with space-based relays to transport significant volumes of renewable energy.

1. Step 1: Electricity from a source on Earth is converted into microwaves and transmitted in a collimated beam to a relay satellite.
2. Step 2: In space, a constellation of orbiting satellites forms a global power grid. The beam is electronically steered.
3. Step 3: Satellites redirect the power beam to the instructed locations, such as one or more satellites, or one or more locations on Earth.
4. Step 4: Back on Earth, the incoming electromagnetic beam is converted back into electricity. A communication signal can also be encoded onto the energy beam, allowing information to be assigned to the energy beam for tracking and transparency purposes.[50]

Financial Review wrote in October 2022 that Emrod has raised $3.3M seed capital via its founder, the New Zealand government, PowerCo and US-based crowdfunding and angel investors.[51] This includes over $1M raised via crowdfunding in 2021.[49]

In May 2023, Emrod announced joining ESA BIC Bavaria and setting up up an office in Munich, Germany, close to partners at DLR, Airbus, OHB, and others. They also stated that they are targeting 2025 to commence in-orbit testing.[52]

4.13 EnergySpace Company

EnergySpace, founded in 2020 in the USA, is a space solar and power beaming company that would like to safely and considerably accelerate the world's transition to sustainable energy.[53] However, in 2022, it was being restructured into an apparel brand.[54]

4.14 Entropy Research and Development

Entropy was founded in 2017 in India to build a constellation of spacecraft for wireless power transmission among satellites.[55] However, they are considered to be dormant after pivoting to consulting.[56]

4.15 Eternal Light Photonics Corp

Eternal Light was founded in 2020 in Canada. In 2021, Astrolight, a collaboration between Astrobotic and Eternal Light, won $50,000 for its wireless mobile power beaming solution from NASA's Watts on the Moon challenge Phase 1.[57] In 2021, they were accepted to Moonshot incubator program.[58]

Eternal Light participated in the Space stream of Creative Destruction Lab cohort 2022/2023 with description "Eternal Light is developing hardware and software to wirelessly charge robotic assets on the Moon (landers, rovers). Their proprietary technology allows them to charge assets from orbit, enabling a scalable energy grid. Their service will break the energy bottleneck that limits lunar missions to a 14-day lifetime. By establishing the lunar power grid, customers will be able to 100x their mission lifetime and value creation."[59]

4.16 Frazer-Nash Consultancy

Frazer-Nash is a systems, engineering and technology consultancy founded in 1971 with offices in the UK and Australia. In 2020-2021, Frazer-Nash Consultancy undertook study, published by the UK's Department for Business, Energy and Industrial Strategy, which considered the technical feasibility, cost and economics of Space Based Solar Power (SBSP).[60,61]

In early 2022, ESA commissioned two cost vs. benefits studies from Frazer-Nash and Roland Berger, which were finished in Aug 2022.[4] Frazer-Nash based their study on the CASSIOPeiA SSP concept.

In September 2023, Frazer-Nash announced partnership with Space Solar to provide expertise in a wide range of disciplines including concept design and engineering analysis.[62]

However, it is currently unclear what kind of long-term interests they have in developing their own space solar power plants.

4.17 International Electric Company (IECL)

International Electric Company Limited (IECL) was founded in 1999 and it designs designs microwave and millimeter wave technologies that have a host of immediate applications, in particular for sustainable & renewable energy. Longer-term aim is to enable grid-scale zero-carbon energy through IECL's unique space solar power concept. They intend to provide gigawatt-scale renewable energy delivered direct to the point of need.[63]

The Chief Engineer, Ian Cash, is known for creating the CASSIOPeiA (Constant Aperture, Solid-State, Integrated, Orbital Phased Array) space solar power concept, which was first published in 2017.[64–66]

4.18 Light Mirror (UAB "Saules sildymo architektura")

Light Mirror is a startup from Lithuania founded in 2019 and designing low-tech reflective panels to improve natural lighting in buildings.[67]

During 2023, they have been working on Light-Mirror Sunlight beam module, which is a mirror to redirect Sunlight from Earth to space for space debris re-entry. Large field of mirrors will be used to collect and concentrate sunlight onto a beam-forming system, creating a highly focused beam of light that is redirected towards space debris. During regular times, the facility will keep a dual use by producing energy.[68]

4.19 Litepulse

Litepulse was founded in 2022 in the USA to create the very first remote power network in space.[69]

Litepulse is building a remote power network in space and the cislunar environment with the aim of providing scalable power to all vehicles in space. The company is building a meshed energy grid powered by the Sun. Goal is to provide more efficient power to satellites, space stations, and additive manufacturing in LEO, GEO, and cis-lunar space.[70]

In December 2022, Orbit Fab and Litepulse announced the signing of a Letter of Intent. Orbit Fab will provide RAFTI units and propellant for Litepulse's power plants. Litepulse will provide power to Orbit Fab in order to enable Orbit Fab to pursue in-situ resource utilization (ISRU).[70]

In June 2023, Spaceium and Litepulse signed LoI to use Litepulse tech to power Spaceium logistics hubs in space.[71]

4.20 Lumi Space

Lumi was established in the UK in 2018. The initial idea was to use lasers to provide power to satellites from Earth. However, they pivoted to laser ranging technology to spot, characterise and precisely track objects in orbit.[72]

4.21 Metasat

Metasat UK was founded in 2020 and specialises in space-based solar power (SBSP) and space sustainability. Goal is to develop SBSP technologies and provide services designed to lessen the environmental impact of the space industry itself through Life Cycle Assessment (LCA).[73]

In a paper at IAC 2023, Metasat's solution was mentioned "this paper will outline the technical details of a novel Sandwich Type SPS concept publicly for the first time. The Multi-domain Operations using Rapidly-responsive PHased Energy Universally Synchronized (MORPHEUS) SPS concept presents an elegant alternative SBSP option, which is currently being pursued commercially by Metasat. It is composed of identical recyclable satellites, each of which have sandwich panels consisting of a microwave transmitter on one side and solar cells on the other, between DC to RF convertors."[74]

4.22 Moliri Space Energy

Moliri was established in 2023 and aims to build space solar power stations to produce electricity with applications in both terrestrial and space markets. They were accepted to Luxembourg's ESRIC Startup Support Programme III September 2023.[75]

4.23 Northrop Grumman

Northrop Grumman Corporation is an American multinational aerospace and defense technology company with about 95,000 employees.[76]

In 2015, Northrop Grumman signed a sponsored research agreement with the California Institute of Technology (Caltech) for the development of the Space Solar Power Initiative (SSPI). Under the terms of the agreement, Northrop Grumman will provide up to $17.5 million to the initiative over three years.[77]

In 2018, The U.S. Air Force Research Laboratory (AFRL) awarded Northrop Grumman a $100M contract to develop a payload to demonstrate key components of a space solar power system. Called Arachne, it could prototype a space-based system to provide solar power to remote military bases.

The Space Solar Power Incremental Demonstrations and Research (SSPIDR) is scheduled to launch in 2025 to show the capability of beaming RF energy down to the planet. In 2022, they announced the successful demonstration of the ability to beam radio frequency energy toward various antennas by steering the beam.[78]

4.24 OHB

OHB was founded in 1958 in Germany. They performed an aircraft charging constellation study with TU Munich and Fraunhofer ILT & ISE.[79]

In 2022, they supported Roland Berger in the cost versus benefit study based on the John Mankins SPS-Alpha concept.[4,79]

4.25 Orbital Power Corporation (OPC)

Orbital Power was established in 2011 in the UK by Philip Owen to generate safe, clean, reliable energy from space.[80] They were planning to use thin-film solar cells.[81] It was dissolved in 2016.[82]

The space segment of their system comprises of Independent Solar Energy Satellites working together to form a single microwave power beam. The baseline design has 10 tonne satellites, with cloud sizes ranging 12 to 300 satellites depending on power required in a particular beam. Each satellite is comprised of a core, a photovoltaic array and a microwave transmission array. The photovoltaic array is composed of thin-film solar cells, supported by a UV-cured inflatable composite frame. The microwave transmission array is composed of small, independently controlled transmitter/processor elements. The power beam is a large 5.9 GHz microwave radio signal that is tightly focused to arrive at a relatively small 'footprint' on Earth.[83]

4.26 Overview Energy

Overview Energy is a VC-backed aerospace startup founded in 2022 and based in the US. Overview is solving fundamental problems in aerospace manufacturing, GNC, and space power systems and will be building a constellation of large, deployable satellites. They aim to build the most economical spacecraft ever flown to GEO, at unprecedented scale.[84]

They seem to be in stealth mode but it is known to be related to space solar power and/or power beaming. PitchBook says they raised $6.8M seed in July 2023[85] while Crunchbase says they raised $3M seed in July 2022.[86]

4.27 Paraloon

ParaLoon was founded in 2023, but were also active in the autumn of 2022, and develops inflatable "parabolic balloon" concentrator photovoltaic (CPV) structures for a sustainable energy solution in and from space. The purpose of these structures is to collect solar energy for applications in space and on Earth. Applications in space would include satellites, space stations, habitats or mission vehicles. On Earth, these structures could be used for remote areas, campsites or mobile applications. The ParaLoon system combines innovative polymeric, inflatable structures and photo-voltaic technologies for the efficient conversion of both light and heat.[87]

4.28 Photonicity

Photonicity was founded in 2019 in Singapore and they aspire to build the various building blocks that would enable cost-competitive space-based solar power and interstellar exploration.[88] According to profile in F6S, they are developing wireless power transmission technology that would be a key enabler for the centralized space power grid.[89]

They have been awarded ESA study titled "Photo-irradiation annealing of radiation-induced degradation of multijunction solar cells for space-based power plants". Their early technology development project aims to develop a method to recover solar cells that have been degraded by radiation. Fixing these cells in orbit could significantly increase the lifetime of a solar power satellite.[48]

4.29 PowerLight

PowerLight was founded in 2007 as LaserMotive. Since then, PowerLight has set three world records for beaming power over light, won two NASA government awards and advanced five generations of technology systems. They are the first team to develop technology platform that demonstrated transfer of 400 watts over 1 kilometer.[90] According to Crunchbase, they have raised over $4.1M but have more in grants.[91]

In 2009, they won $900,000 in a NASA-sponsored contest to power cable-climbing robots.[92] In 2021, they were finishing a $9.5M project for the U.S. Naval Research Laboratory. In 2019, PowerLight showed that its power-beaming system can transmit 400 watts of power. In 2020, it demonstrated a lightweight power receiver suitable for drones.[93]

4.30 PowerSat Corporation

PowerSat was founded in 2001 in the US and describes itself as a pioneer in generating safe, clean, reliable energy from space. Solar energy would be captured via satellites (powersats) and transmitted wirelessly to receiving stations around the globe.[94–96]

In 2009, PowerSat said it has filed the application for a patent related to "BrightStar" satellites, which it envisages being coupled wirelessly in space to create large clusters of independent solar arrays that contribute to a single transmission beam.[97] They planned to have a BrightStar on orbit for demonstration purposes in the 2017-2018 range.[98]

The inflatable BrightStar weighs about ten tons. At stowed, it would be 4.5 meters in diameter by 11.3 meters long. Deployed, each BrightStar looks like two thin plates, supported inside the rim. The larger of these two "disks" is the photovoltaic array and is 350m in diameter, separated and supported by an inflatable torus with a diameter of two meters. The smaller disk is the transmitter, about 100m in diameter, also thin-film in construction supported by the same inflatable outer rim. Each BrightStar will generate about 17MW on orbit.[98]

4.31 ReBeam

ReBeam was founded in 2016 in the USA and they were building the first Wireless Energy Network for grids using satellites.[99] They are considered dormant as the last social media post was in 2016 and website has been redirected to Vrisva Space.

4.32 Reflect Orbital (Tons of Mirrors)

Reflect Orbital was founded in 2021 to build a constellation of satellites to reflect sunlight onto existing solar farms at night. By selling sunlight, they increase the output of existing infrastructure.[100] In 2022, they were called Tons of Mirrors.[101]

4.33 Ronald Berger

Roland Berger is a global consultancy with offices in all major markets and industries.[102]

In early 2022, ESA commissioned two cost versus benefits studies including from Roland Berger.[4]

However, as with other consultancy-focused entities, it is currently unclear what kind of commercial interests they have and whether they plan to lead the development of space solar power plants.

4.34 Satellite Applications Catapult

In January 2023, it was announced that The Catapult secured almost £500k in funding from the UK Space Agency to kick-start research and development into Space-Based Solar Power (SBSP) system.[103]

In August 2023, Satellite Applications Catapult is forming a partnership with Space Solar, which is a spinout from the Catapult since April 2022. The partnership will be delivered through provision of technical expertise and other support.[104]

4.35 Shimizu Corporation

In 2013, Japanese construction firm Shimizu unveiled a LUNA RING concept to build a solar array around the Moon's equator and send the power to Earth with construction starting as early as 2035.[105,106]

4.36 Sirin Orbital Systems

Sirin Orbital Systems was founded in 2019 in Switzerland and focuses on the development of advanced enabling technologies notably for Space-based Solar Power (SBSP) / Wireless Power Transfer (WPT) applications and others.[107] They have an ESA-funded study on "Development of Millimetre Waves Wireless Power Transfer (WPT) System for Lunar Rover Explorations". This project will focus on developing technology for the wireless transfer of power as the intermediate goal of supplying energy to the Moon.[48]

4.37 Solar Space Technologies

Solar Space Technologies (SST), is an Australian company founded in 2019 that is planning the development and commercialisation of the technology for base load solar power generation from outer space, including the deployment of solar power generation satellites, ground receiver sites and associated infrastructure to provide base load energy for Australia and the world. Goal is to eventually develop a total capacity of at least 18 gigawatts of electricity.[108]

Notably, their website lists John C. Mankins as a director, who is widely known in the industry for his SPS-Alpha concept and also by publishing a book "The Case for Space Solar Power" in 2014.[108]

4.38 Solar System Resources Corporation

Solar System Resources Corporation is a space mining startup from Poland founded in 2020. They write on the website that from December 2021 they started lobbying for the development of space energy (SBSP) in Poland and Europe.[109]

4.39 Solar.Space

Solar.Space was a concept from the UK in 2018 to provide wireless energy to other satellites.

4.40 Solaren

Solaren was founded in 2001 to make space solar power reality. In 2009, California's biggest energy utility (Pacific Gas & Electric) announced a 15-year deal to purchase 200 megawatts of electricity that would be beamed down to Earth from outer space, beginning in 2016. Solaren's system would be "competitive both in terms of performance and cost with other sources of baseload power generation."

Gary Spirnak (CEO), said the company consisted of about 10 engineers and scientists, and plans to employ more than 100 people in a year. "The impetus for forming Solaren was the convergence of improved high-energy conversion devices, heavy-launch vehicle developments, and a revolutionary Solaren-patented SSP design that is a significant departure from past efforts and makes SSP not only technically but economically viable."[110]

In June 2023, they announced raising $2.5M in an initial Series D round.

4.41 Solestial

Solestial, previously Regher Space, was founded in 2015 and raised $10M seed in 2022. Solestial is developing thin-film, flexible, mass-manufactured, radiation-hardened and low-cost silicon solar cells and solar blankets.[111,112]

Solestial has not announced their own space solar power plans but the illustrations on their website show extremely large solar arrays.[111,112] Perhaps they are out-of-scope for this survey at this time, but it is likely that their solar cells would be a critical part of many space solar satellite designs.

4.42 Space Applications Services

Space Applications Services was founded in 1987 in Belgium. They develop systems and payloads for the ISS, on-orbit servicing and lunar destinations. They also develop robotic and rover systems and many other solutions.[113]

They were awarded an ESA funded study on "Skybeam: Assembly of a Space Solar Power system with European Technologies". The takes a look at the assembly of an SBSP station based on strategic technologies being developed in Europe. The concept foresees multiple multi-axis robots that create

the vast (kilometre-scale) structural elements of solar power satellites by mounting standardised construction elements together.[48]

4.43 Space Energy

Space Energy was incorporated in Switzerland in 2008 and by 2010 it had grown to have branches in five countries. Funding totalled about $4M plus support from private individuals. In December 2010 to 2013, they continued to pursue ground and space-based projects with many milestones achieved. Additionally, Space Energy also sold various IT equipment. Shortly afterwards, the company suffered a major loss having been targeted by organized criminals who posed as legitimate buyers of one of the IT deals. This caused a debt to Space Energy from which they did not recover.[114] There are also alternative viewpoints of what happened.[115]

4.44 Space Power

Space Power is based in the UK and was founded in 2019. They are developing technology required to centralise energy generation and distribution in space, offering spacecraft a more reliable and efficient source of energy. Their optical power beaming technology will wirelessly transmit energy over long distances, with minimal losses. They say the ability to transfer power from one spacecraft to another will alter the possibilities – enabling new missions far from the Sun.[116]

4.45 Space Solar

Space Solar, a spinout from the Satellite Applications Catapult in the UK, has been operating since April 2022. They are planning a demonstration of megawatt-scale power beamed from space by 2029.

Since 2022, Space Solar has kick-started the development program for the first operational Gigawatt scale space-based solar power system, CASSIOPeiA. They are now focusing on the rapid delivery of this program, including the completion of its first wireless power demonstrator, which is an important step in their 12-year delivery plan.[117]

It was reported in early 2023 that Saudi Arabia's NEOM and UK government invested $4.3M.[118,119]

4.46 Spacefaring Services

Spacefaring Services was an early stage startup likely founded in 2014. They write on their website that the technical assertion has been made that space-to-space and space-to-Near Earth Object (NEO) surface power beaming technology can be matured to support both mission enhancing and mission enabling applications. The development, marketing, and infusion of the SBSP technology for space-to-space and space-to-NEO applications is a joint project with Barnhard Associates (Gary P. Barnhard).[120]

In 2021, J. Rauscher, CEO, published a paper "USA Public-Private Prototype Power Beaming Infrastructure for Disaster Response and Recovery".[121]

4.47 Spacians

Spacians was founded in 2019 and was based in Sweden and India. The website is now offline but in 2021 they had 2 sections about space solar power.

"Space Power Station (SPS) - A power station using flywheel energy storage to provide continuous electricity to space probes through efficient wireless technology. It will enable spacecraft to carry smaller solar panels and batteries."[122]

"Space Powered Atmospheric Satellite Technology (SPAS-Tech) - Receives a continuous wireless electricity supply from the space power station so that it can work more efficiently compared to current atmospheric satellites (HAPS, UAVs)."[122]

4.48 Stellarion Energy (STELLA)

Stellarion was an India-based startup likely from 2020. They were committed to eradicate energy crisis with a solution from space. However, the website and LinkedIn have been deleted.[123]

4.49 STELLS

STELLS was founded in 2021 in Canada and is developing MPR-1 Mobile Power Rover, which is a medium-size rover scheduled to launch in 2024 to the South Pole of the Moon and provide power to other missions. The idea, as per their Youtube Moon Mission trailer, is to leave a box in a shadowed crater, which would be connected via cable to their rover with large solar panels, but the customers would use short-distance wireless power transfer.[124,125]

4.50 SunCubes

SunCubes started in Italy in 2021 and aims to develop the future space energy infrastructure through an in-space satellite recharging system to maximize performance. Goal is to have the first four satellites in space by 2026 and capable of powering around 90 users spacecraft.[126,127]

4.51 Thales Alenia Space

Thales Alenia Space is a joint venture with sites in 9 European countries.[128]

Thales Alenia was awarded ESA-funded study called "Receiv'Air – Bypassing of atmospheric attenuation for SPS with airborne receiver" looking into using an airship to receive a high frequency beam at a high altitude.[48]

In April 2023, ESA awarded study contracts to develop new reference-design space solar power architectures for large-scale terrestrial use to Arthur D. Little and Thales Alenia Space Italy.[41]

4.52 The Lunar Grid

The Lunar Grid was established in Luxembourg in 2021. They are developing wireless energy transmission, both for terrestrial and space applications. The transmission will be over a free-space optical laser link and can reach over several kilometres. A power receptor will convert the laser light back into electricity. Their aim is to power all lunar missions and provide them with continuous access to energy.

However, first focus will be on using the technology on Earth for drones to extend their flight time. They said well that if they had product standing on the Moon today, there would be no customer.[129,130]

Thus, since early 2022, the founders are focused on the wireless drone charging startup SkyGrids.

4.53 Virtus Solis

Virtus Solis was founded in 2018 in the USA. They say they have designed the world's first space-based solar power energy generation system able to directly compete with all forms of energy. The process and details are:[131,132]

1. Solar power gathered in space by small satellites with high efficiency solar panels. Each 1.65 m satellite delivers 1 kW of power to ground.
2. Satellites are grouped into massive arrays, 100,000 satellites for 100MW, allowing for a highly scalable energy platform up to multi-GW level.
3. Satellites are in sunlight all of the time with long dwell time over the northern/southern hemisphere due to orbital characteristics. Using highly elliptical Molniya orbit constellation.
4. Solar energy is converted to 10 GHz microwaves to beam energy to ground - rectennas gather microwave energy and convert to electricity.[132]

They won $200,000 in 2022 as one of the 7 winning teams of Phase 2, Level 1 of NASA's Watts on the Moon Challenge.[133] The challenge describes delivering energy across 3 km from a variable source and delivering it to a load at the other end. They solved it with their core wireless power transfer technology and a novel energy storage system.[132]

In March 2023, they demonstrated power beaming live over 100 meters. It consisted of one power satellite of 1.92m aperture, which had 6400 transmitting antenna elements. One receiving antenna (rectenna) of 1.32m x 1.62m aperture had 1944 receiving antenna elements.[134]

In May 2023, they were accepted to Seraphim Space Accelerator.[135] In June 2023, they together with the University of Bristol in the UK were awarded £353,000.[136]

Virtus Solis has not publicized fundraising amounts but they are likely to be one of the best funded, and among some of the furthest along, space solar power startups.

4.54 XISP (Xtraordinary Innovative Space Partnerships)

XISP was founded in 2012 and is a cislunar mission development company.[137] They have published reports and articles on space solar power since at least 2016.[138]

In 2017, Gary Barnhard, CEO, published an article "Space-to-Space Power Beaming (SSPB) - A Commercial ISS Technology Development, Demonstration, and Deployment (TD3) Mission".[139]

In August 2018, they published a proposal titled "ISS Space-to-Space Power Beaming: Fostering a Cislunar Electrical Power and Ancillary Utilities Service".[140]

5. STATISTICAL OVERVIEW

Statistical overview has been created of the 52 commercial entries from Table 2 included in this space solar power survey.

5.1 Founding Years with Status

Figure 3 illustrates the organisation founding years and their current statuses in relation to SSP.

As seen from the figure, visible increase in entities starts from around 2012. Further increase begins from 2018, which is after the SpaceX Starship announcements, which is considered to be the primary enabler of space solar power assuming the forecasted launch price reductions will happen.

No commercial entities have sent space solar power demonstrations to space as of September 2023. Caltech did in early 2023 but they are a non-commercial organisation. This also means none are active and those categories are missing from the legend because there are no such entries in the database.

5.2 Funding Levels with Categories

Figure 4 plots the funding amount in specified categories. The funding levels are the total amount announced and the exact investments for space solar power may be unknown in case of larger companies.

"Yes, but amount unknown" commonly means an established company, but it has not been made public of how much they are investing in SSP. The "Unknown" category is for entities which have not announced funding and it is likely they have no or very small amount of capital.

Yes, but amount TBD have for example Airbus, Northrop Grumman, OHB, Space Applications Services and Thales Alenia Space.

Category $10-50m includes Solestial, but it is currently unknown whether they plan to develop their own space solar power plants in the future or remain a supplier of solar cells and solar blankets.

Category $5-10m includes Overview Energy.

Category $1-5m includes Aquila Earth, Emrod, Powerlight, Solaren, Space Energy and Space Solar.

Category $0.1-1m includes e.g. Astrostrom, Eternal Light, STELLS, The Lunar Grid and Virtus Solis. Virtus Solis may have considerably more funding but has not been announced publicly.

Category <$0.1m has Space Power and ParaLoon.

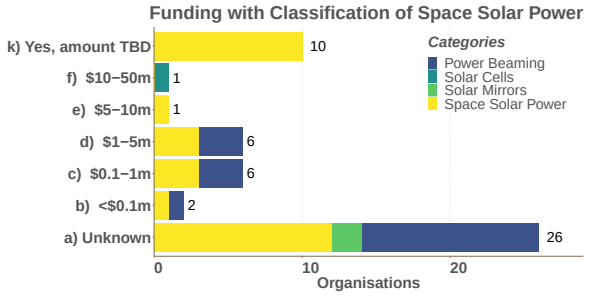

Figure 4: Funding Levels with Classification of Space Solar Power Commercial Activities

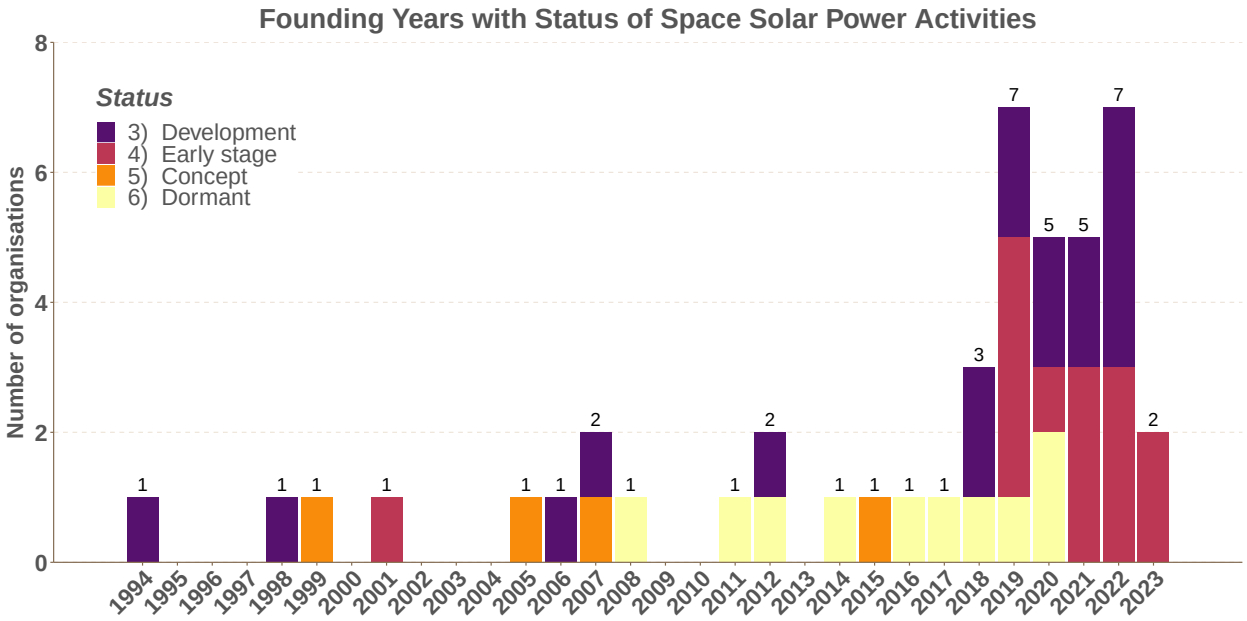

Figure 3: Founding Years with Status for Space Solar Power Commercial Activities

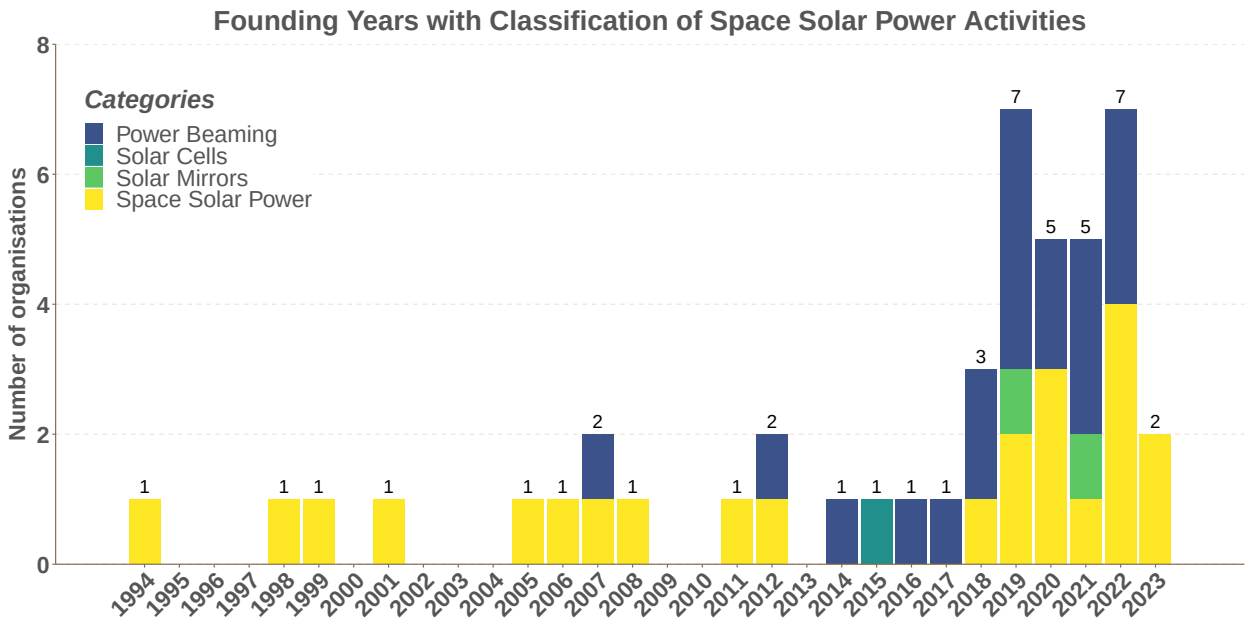

Figure 5: Founded Years with Status for Space Solar Power Commercial Activities

5.3 Founding Years with Categories

Figure 5 gathers the founding years of the organisations with the initial activity categories. The earliest known dedicated space solar power company is Solaren founded in 2001. Entities founded earlier than 2001 were or are active in other activities.

The figure shows that the dream of making space solar power happen has continued through the 1990s and 2000s. Then the idea of power beaming emerged for different commercial space applications and likely requiring less capital. The growth in the number of entities starting from 2018 is expected to continue.

5.4 Categories for Initial Activity Focus

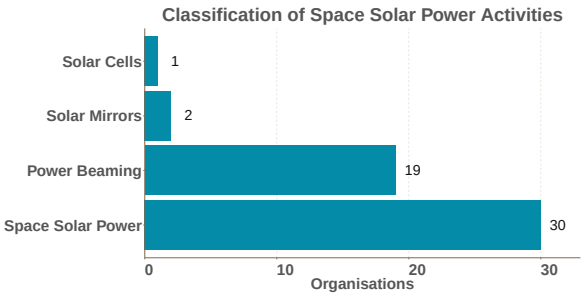

Figure 6: Categories of SSP Commercial Activities

Figure 6 shows the distribution of the 52 surveyed entities by the high-level category assigned for the initial activity to give more contextual information. Solestial is under Solar Cells. Solar Mirrors includes Reflect Orbital. Organisations under Power Beaming are initially focusing on wireless power transfer, e.g. to beam power to satellites in LEO or to spacecraft on the surface of the Moon.

5.5 Funding Levels with Status

Figure 7 plots the funding amounts in specified levels together with the activity status. Most founded companies are actively in development as expected. Space Energy is the organisation, which claimed about $4M in funding, but shut down around 20131. Most of the other dormant companies likely never raised private funding. Solestial with the highest known funding amount is marked as Concept. Many larger companies, most of which as of now have only performed concept studies, are marked under the "Yes, but amount TBD" funding level.

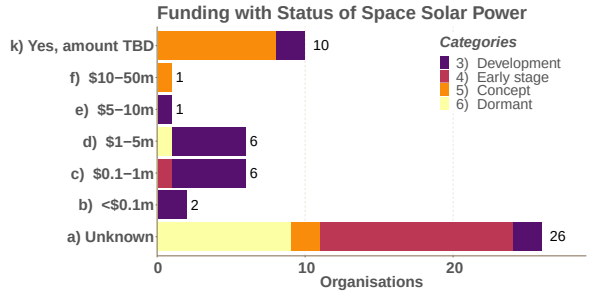

Figure 7: Funding Levels with Company Status of Space Solar Power Commercial Activities

5.6 First Space Launches

Figure 8 collects the first space launch years for space solar power technology demonstrations.

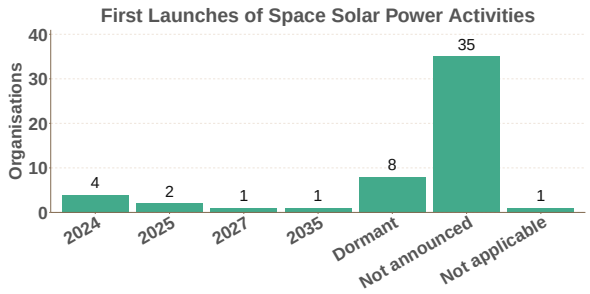

Figure 8: First Launches of Space Solar Power

Based on the figure, only a few have announced planned years for maiden launches to space. This correlates to most companies being in Early or Concept stages with limited or no hardware development and relatively small amounts of funding.

In 2024, launches have been announced for Reflect Orbital, Solestial, Space Power and STELLS. In 2025, maiden flights will be for Emrod and Northrop Grumman. Solar Space Technologies announced first launch in 2027.

Shimizu's LUNA RING could start to be built from 2035 but likely only a concept as of now.

Dormant is likely much higher than shown and will continue tracking their progress or lack of it.

Not announced are for example Virtus Solis and Overview Energy. Older companies, whose dates have passed, are now marked as "not announced".

5.7 Geographical Distribution

Figure 9 shows the distribution of space solar power commercial organisations. Many entities have multiple offices and the map shows all of them. The written examples below are for headquarters.

USA has 15 entities including for example Northrop Grumman, Overview Energy, Powerlight, ARTEMIS, Reflect Orbital, Solaren, Solestial and Virtus Solis.

UK has 9 entities e.g., International Electric Company, Space Power, Space Solar and Metasat.

Canada has 3 entities including 3K SpaceTech, Eternal Light and STELLS.

Switzerland has 3 entities including Astrostrom, Sirin Orbital Systems and Space Energy.

France has Airbus. Germany has OHB. Italy has Thales Alenia Space.

ParaLoon is based in Belgium. Solar System Resources Corp is in Poland. Alvior is from Norway.

India has 3 organisations including Entropy, Spacians and Stellarion Energy (STELLA).

Australia has 2 startups, Aquila Earth and Solar Space Technologies.

Emrod was founded in New Zealand but now also has an office in Germany.

Celestia Energy is based in the UAE.

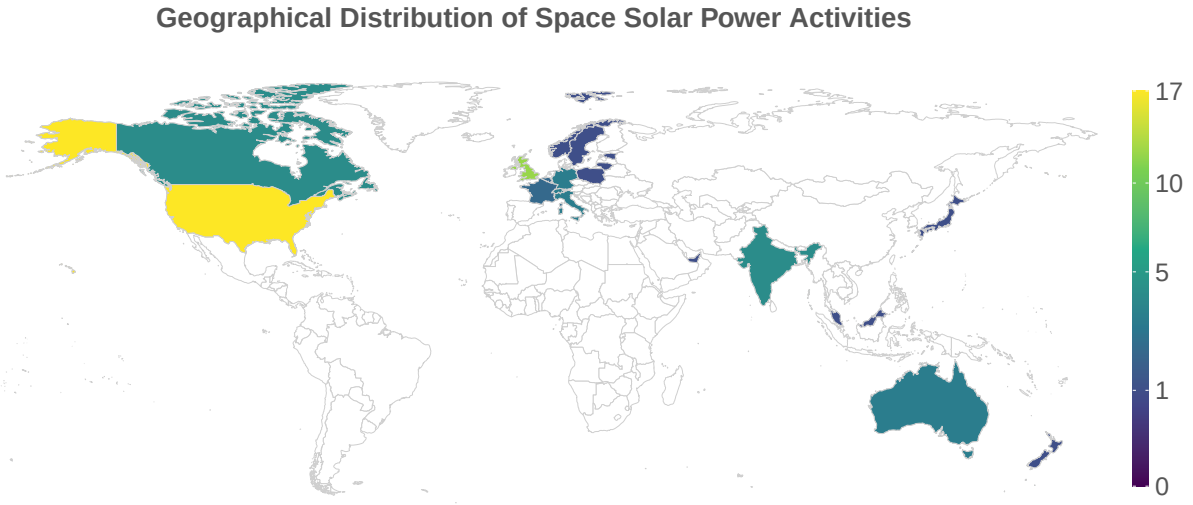

Figure 9: Geographical Distribution of Space Solar Power Commercial Activities

6. NON-COMMERCIAL LANDSCAPE OF SPACE SOLAR POWER

There are also numerous universities developing various building blocks for space solar power but most of them have not been surveyed yet. Many of them have been awarded studies by ESA[48] or by the UK[141] in the recent years. Please note this section does not aim to be exhaustive.

6.1 Canada

SHARP (Stationary High Altitude Relay Platform) was an experimental aircraft using beam-powered propulsion designed by the Communications Research Centre Canada and built by the University of Toronto Institute for Aerospace Studies in the 1980s.[142]

SPACE Canada (Solar Power Alternative for Clean Energy) is a not-for-profit organization dedicated to the promotion of solar energy from space. They held a three-day symposium in 2009 "From the Sun to the Earth" and have organised The International Space Solar Power Student Project Competition since 2016.[143,144]

6.2 China

Deng Xiaoci and Fan Wei wrote in April 2023 that China's research and development into its own space-based power station has accelerated since a proposal was approved in 2013. More than 130 experts from 16 departments and agencies spent a year conducting a feasibility study in 2014.[145]

In June 2022, Andrew Jones wrote in length about China's plans in SpaceNews. The China Academy of Space Technology (CAST) plans to conduct a "Space high voltage transfer and wireless power transmission experiment" in LEO in 2028. The satellite will generate 10 kilowatts and test power transmission across distances of 400 km from orbit. The plan also involves building infrastructure on the ground for receiving energy transmissions. The 2028 phase 1 test will be followed by phase 2 in 2030, launched into geostationary orbit. Phases 3 and 4 would be in 2035 and 2050, will increase energy generation first to 10 MW and then to 2 GW.[146,147]

Dr. Shi-Wei Dong presentation at the IAC 2023 conference contained many (numerical) details.[148]

6.3 European Space Agency

According to ESA's SBSP history, in 1979 ESA performed its first study of the topic: "European Aspects of Solar Power Satellites". In 1999, ESA included Space Based Solar Power in a study of space utilisation. In 2003, ESA's Advanced Concepts Team commenced the European Solar Power from Space Programme, assessing the validity and viability of solar power from space concepts.[149,150]

ESA re-started exploring space solar power in 2020. In early 2022, ESA commissioned two cost versus benefits studies from Frazer-Nash Consultancy and Roland Berger.[4]

In November 2022, the SOLARIS 2-year preparatory initiative was announced to fund the development of relevant technologies and studies for future decision making.[151,152]

In April 2023, ESA awarded study contracts to develop new reference-design space solar power architectures for large-scale terrestrial use to Arthur D. Little and Thales Alenia Space Italy.[41]

In July 2023, Astrostrom completed their ESA-funded study investigating the feasibility of a "Greater Earth Lunar Power Station" (GEO-LPS) manufactured on the Moon and assembled at the Earth-Moon Lagrange Point 1 to provide power to Moon.[43]

In early October, ESA organised the International (On-line) Conference on Energy from Space.[153]

6.4 Japan

In 1983, Japan conducted the Microwave Ionosphere Nonlinear Interaction eXperiment (MINIX) on a sounding rocket. Two magnetrons were used to emit 2.45 GHz microwave to make a simulated condition of power transmission from an SPS to a ground station. Measurements were conducted by the daughter unit, which was separated slowly from the mother unit. In 1993, they conducted a sounding rocket experiment using phased array antenna for more accurate power transmission in space.[154,155]

In 1992, Canadian SHARP research was picked up at Kyoto University. Their MILAX (Microwave Lifted Airplane Experiment) vehicle had two new features. The rectenna on the aircraft was embedded in the wings and tail surfaces. The broadcast antenna was a phased array. The system was tested on a driving truck with MILAX following.[142]

In 1995, Energy Transmission toward High altitude long endurance airship ExpeRiment (ETHER) was conducted by Kobe University. A 2.45 GHz/ 10 kW microwave beam was transmitted to an airship flying approximately 45 m above the ground.[142,156]

In March 2015, Mitsubishi Heavy Industries (MHI) conducted a ground demonstration testing of wireless power transmission. In the ground demonstration test, 10 kilowatts (kW) of power was sent from a transmitting unit by microwave. The reception of power was confirmed at a receiver unit located

at a distance of 500 meters away. MHI conducted the ground demonstration testing based on an agreement with Japan Space Systems carrying out the "2012 Solar Power Wireless Transmission Technology Development Project."[157]

SSP has been included into the government's Basic Plan on Space Policy since formulation in 2009.[155] Japanese public-private partnership is aiming to run a trial around year 2025.[158,159] Dr. Koji Tanaka talk at IAC 2023 conference was very informative.[160]

6.4.1 Japan Space Systems

Japan Space Systems was founded by the Japanese Ministry of Economy, Trade and Industry in 1986 and it got its name after a merger in 2012.[161] They have designed a reference architecture, studied wireless power transfer to rovers, studied life-cycle CO2 emissions, have performed microwave power beaming demonstrations and more.[162]

Power beaming experiment project from the LEO satellite to the ground called "Onorbit experiment of HIgh-precision beam control using small SAtellite for MicrowAve power transmission (OHISAMA)" was started in December 2022. The power transmission satellite has power transmission panels, and the ground system consisted of the receiving devices spread to measure the beam control capability of the power transmission panels, and also large parabolic antenna to demonstrate the power transmission.[163]

6.4.2 JAXA

Japan commenced its SSPS research activities in the 1980s. Under leadership of the Institute of Space and Astronautical Science (current JAXA ISAS), an industry-government-academia research team introduced a conceptual design of a 10,000 kW-class "SPS2000" in the 1990s. In the 2000s, JAXA and the Ministry of Economy Trade and Industry (METI) studied a million kW-class SSPS concept.[164]

6.4.3 Space Solar Power Society

Established in 2014 by Kyoto University Professor Emeritus Matsumoto as the first academic society with goal to realize space solar power by promoting academic research and industry-government-academia collaboration.[165]

6.5 Netherlands

Energy from Space Foundation was established in 2012 to promote energy from space and works on a proposal to launch the first proof-of-concept.[166]

6.6 Russia

The Znamya project was a series of orbital mirror experiments in the 1990s that intended to beam solar power to Earth by reflecting sunlight. Constellations were imagined, with one having up to 100 reflectors of 400 meter diameter, to illuminate cities in northern latitudes.[12,167–169]

Znamya 2 had a diameter of 20 meters and was deployed February 1993. Due to the imperfect shape, the estimated brightness was rather about 1 full moon. Next experiment, Znamya 2.5 mission failed to deploy in 1999. It had 25 meter reflector and light spot on Earth would have been 5-7 kilometers with brightness of 5-10 full moons. Znamya 3 was planned to be 60-70 meters but it was cancelled. SolarKraft was a spacecraft concept equipped with a solar sail solar reflector or photovoltaics.[12,167–169]

6.7 Saudi Arabia

NEOM Space is exploring the possibility of using solar power from space to supply carbon free energy for its projects. According to The Times, NEOM and the UK government invested $4.3M into Space Solar, a company in the UK.[118]

6.8 South Korea

Korean space solar power satellite was published at IAC 2019 and in 2022, a 50 meter wireless power transmission was demonstrated on the ground.[170] In 2022, Dr. Joon Min Choi from KARI and Dr. Sang-Hwa Yi from KERI proposed a system of two small satellites using formation flight for wireless power transmission. In 2023, they presented a LEO space solar power satellite system to transmit electricity to the ground, while considering technology readiness and budgetary availability in Korea.[171]

6.9 United Kingdom

During 2020-2021, Frazer-Nash undertook a study, published by the UK's Department for Business, Energy and Industrial Strategy, which considered the technical feasibility, cost and economics of Space Based Solar Power (SBSP).[60,61]

In March 2023, UK Launch Services Limited completed a comprehensive Regulatory Roadmap towards a Space-Based Solar Power (SBSP) on behalf of Space Solar Ltd and the Satellite Applications Catapult.[172]

In June 2023, the UK Government's Department for Energy Security and Net Zero and the UK Space Agency announced £4.3M in grants to space solar power technologies.[141,173]

6.9.1 Space Energy Initiative

The Space Energy Initiative started in November 2020 and includes energy and space organisations, industry, HM Government, academia and research agencies, promoting and advancing the development of Space Based Solar Power for the benefit of the UK and partner nations. The founder, Martin Soltau, is now the Co-CEO of Space Solar and he was previously at Frazer-Nash.[73,174,175]

6.9.2 University of Glasgow

From 2016-2017, Professor Colin McInnes at University of Glasgow was the principal investigator of project "Space-Enhanced Solar Power for Equatorial Regions", which investigated the concept of solar mirrors in an Earth orbit to provide large-scale terrestrial equatorial solar farms with additional solar power during the hours of darkness.[176]

For 2020-2025, Prof. Colin McInnes was awarded €2.5M by European Research Council for project "SOLSPACE: Enhancing Global Clean Energy Services Using Orbiting Solar Reflectors". The project will research a constellation of ultra-lightweight orbital reflectors to illuminate large terrestrial solar power plants, particularly at dawn and dusk, when their output is low but electricity demand and spot prices are high. As a key breakthrough, they will demonstrate new processes to enable the automated in-orbit fabrication of large gossamer reflectors.[177]

6.9.3 University of Strathclyde

University of Strathclyde is also based in Glasgow and has researched space solar power. In 2012, they were part of NASA Institute for Advanced Concepts (NIAC) study led by John Mankins. The project was called SAM (Self-inflating Adaptable Membrane) and idea was to test the deployment of an ultra light cellular structure that can change shape once deployed. The structure is made of cells that are self-inflating in vacuum and can change their volume independently through nanopumps.[178]

In 2020, A. R. Wilson et al. published a paper "A Process-Based Life Cycle Sustainability Assessment of the Space-Based Solar Power Concept".[179]

They have a co-funded project with ESA called "CORES – COllaborative Recycling of End-of-life SPS" studying collaborative robotics solutions to dismantle, replenish and remanufacture large space infrastructures.[48]

6.10 United States

The United States has studied space solar power since the 1970s. The energy shortages of 1973 created interest and in early 1976, the Department of Energy (DOE) and NASA initiated an SPS Concept Development and Evaluation Program.[15]

6.10.1 Breakthrough Initiatives - Starshot

Breakthrough Starshot was initiated in 2016 to advance interstellar travel. The mission includes a ground-based light beamer pushing ultra-light nanocrafts with lightsails to perform a flyby mission of Alpha Centauri in just 20 years from launch.[180,181] While the lasers are ground-based, many relevant technologies are still being advanced.

6.10.2 California Institute of Technology (Caltech)

Caltech announced in 2021 that they received a $100M donation in 2013 to form the Space-based Solar Power Project.[182]

In 2015, Caltech announced a sponsored research agreement with Northrop Grumman, which provided Caltech up to $17.5M over 3 years for the Space Solar Power Initiative (SSPI).[183]

Caltech launched a demonstration mission in January 2023 as a hosted payload on Momentus spacecraft. Wireless power transfer was demonstrated in March. MAPLE (Microwave Array for Power-transfer Low-orbit Experiment) was one of the three key experiments of Space Solar Power Demonstrator (SSPD-1). It consists of an array of flexible microwave power transmitters driven by custom chips that were built using low-cost technologies. MAPLE transmitted power to receivers in space as it features two separate receivers about 30 cm away from the transmitter, and were used to light up LEDs to demonstrate the full sequence of wireless energy transmission in space. They also directed the energy toward Earth, which was detected at Caltech.[184,185]

6.10.3 Citizens for Space-Based Solar Power (C-SBSP)

The purpose of Citizens for Space Based Solar Power is to consolidate existing information, and to generate public support for the development of space-based solar power. The blog was started in 2007 by Rob Mahan.[186]

6.10.4 Colorado School of Mines

In August 2019, the Colorado School of Mines published report titled "21st Century Trends in Space-Based Solar Power Generation and Storage" was pub-

lished.[187] In 2020, the same group published an article on "Feasibility of space solar power for remote mining operations".[188]

6.10.5 DARPA

In 2023, DARPA entered the first phase of the Persistent Optical Wireless Energy Relay (POWER) program, aimed at revolutionizing energy distribution through airborne wireless power transfer. Three teams - led by RTX Corporation, Draper Laboratory, and BEAM Co. - will design and develop wireless optical power relays.[189]

The optical energy relays designed in POWER's phase one will be demonstrated in pods carried by existing aircraft in the project's second phase. Eventually, these new, small, distributed platforms could provide cost-effective aircraft with unlimited range and endurance to support military missions. Each relay design will be evaluated based on accurate and efficient energy redirection, wavefront correction for high beam quality, and throttleable energy harvesting. In the third and final phase of the program, the relays will be demonstrated through an airborne optical pathway that aims to deliver 10 kilowatts of optical energy to a ground receiver that is 200 kilometers away from the ground source laser.[189]

6.10.6 NASA

NASA has funded and participated in numerous studies over the decades starting from 1970s.

During 1995-1997, NASA conducted a far-reaching, preliminary reexamination of the technologies, systems concepts and terrestrial markets that might be involved in future space solar power (SSP) systems, conclusions presented by John C. Mankins.[190]

In 1999-2001, NASA's Space Solar Power (SSP) Exploratory Research and Technology (SERT) program was charged to develop technologies needed to provide cost-competitive ground baseload electrical power from space-based solar energy. The SERT program was established in FY 1999 and continued through FY 2000 by U.S. congressional appropriation. An additional appropriation for SSP was also funded for FY 2001.[191]

In 2017, NASA selected the previously referenced Colorado School of Mines study as one of five economic research studies awarded on space economy.[192]

6.10.7 Naval Research Laboratory

The Naval Research Laboratory (NRL) launched an experiment in 2020 aboard the Air Force's X-37B space plane that captured sunlight and converted it into direct current electrical energy.[78]

In June 2023, NRL's Space Wireless Energy Laser Link (SWELL) experiment surpassed 100 days of successful on-orbit laser operations. Launched in March 2023, this experiment is the first successful laser power beaming in space. It is located on the ISS as part of the U.S. Department of Defense Space Test Program (STP) H9 mission. SWELL has been providing nearly continuously about 1.5 watts at the power beaming receiver's output with an end-to-end efficiency around 11%. The power beaming link distance is 1.45 meters. To NRL's knowledge, in addition to being the first laser power beaming demonstration in space, this also represents the highest power, longest distance, and most efficient power beaming demonstration in orbit of any type.[193]

6.10.8 Power Satellite Economics

Power Satellite Economics is a forum started in 2015 and moderated by Keith Henson, a long-time independent researcher of space solar power.[194, 195]

6.10.9 Space Frontier Foundation

Space Frontier Foundation was established in 1987 and the current project Climate Alliance will bring together a small collective of universities to do research on one aspect of space based solar power.[196]

6.10.10 Space Solar Power Institute

Chartered in 1997, the Space Solar Power Institute is a non-profit educational corporation to educate the public about Space Solar Power and the clean baseload energy transformation which defines why, when and how SSP must be built.[197]

6.10.11 Space Studies Institute

Solar power satellites are an important field for the Space Studies Institute even before Gerard O'Neill started the organization in 1977.[3]

6.10.12 University of Houston

Professor David R. Criswell was an advocate for lunar solar power for over 30 years with an idea to build the Lunar Power System (LPS) on the surface of the Moon and beam the energy to Earth.[198–201]

7. CONCLUSIONS

The energy problem is so large and the market is so large that humanity should take multiple parallel attempts at promising solutions. Abundant cheap green energy could have a big positive impact on the world. Waiting for a specific solution (e.g. fusion) is not the best path, because it may take much longer, or end up having unfavourable economics.

Private and public initiatives of space solar power and space-related power beaming have been surveyed and introduced. Statistical overview of the 52 discovered commercial entities has been created.

Some concluding thoughts and observations about the space solar power landscape and market context:

- Most of the space solar power studies since 1970s have concluded that launch costs must decrease significantly and launch cadence plus mass-to-orbit must improve considerably for space solar power to become economically viable. Optimistic forecasts for the Space Shuttle did not come true but now SpaceX's Starship is on a path to solve them.
- Space solar power and power beaming have a very large terrestrial energy market, which cannot be said for most NewSpace industries.
- Space solar power is now likely an engineering problem, and not a science problem, to create a practical large-scale design, which is sufficiently low-cost to be economically viable.
- It is too early to forecast which space solar architecture, orbit, beaming method (microwave vs laser vs mirrors), configuration etc has the highest probably of succeeding economically. Space history is full of great designs on paper, which have not succeeded in reality. Thermal issues and novel materials are not easy to solve and may require completely new architectures. It is beneficial that many companies are pursuing different solutions. In case of space solar power, pragmatic systems engineering will likely make a big difference.
- One major challenge is the very large up-front investments required to develop and build space solar power systems, which are able to generate revenue and then profit. Hopefully, a very large terrestrial energy market will help to counter that in the eyes of investors.
- One of the most important criteria is the cost of electricity input to electric grid on Earth. Thanks to microgravity, more continuous sunlight etc, energy from space may be cheaper and more beneficial even with all efficiency losses.
- Space-to-space and space-to-Moon or Moon-to-Moon markets may happen first, but because those markets do not exist yet, they are likely to remain limited for the next decade.

Conclusions about the statistical overview of 52 commercial entities in space solar power:

- Target customers may be on Earth, in space (e.g. satellites, habitats), on the Moon (e.g. rovers, landers, facilities) and also beyond (e.g. on Mars, laser sails and solar sails).
- The first dedicated startups to be established seem to be Solaren and PowerSat (both founded in 2001) and Space Energy (started in 2008).
- Majority of the 52 commercial entities are in the early and concept stages. Many are also already dormant.
- Numerous entities have performed studies, but it is unclear how many of them are developing hardware, and intend to develop their own space solar power plants.
- Only a small part out of 52 have announced maiden launches for related technology demonstrations in space. However, first ones may launch as early as 2024.
- Only some out of 52 have raised over $1 million, including Aquila Space, Emrod, Overview Energy, PowerLight, Solaren, Space Energy and possibly also Virtus Solis.
- Emrod and Virtus Solis have demonstrated microwave power beaming terrestrially. PowerLight has demonstrated laser power beaming on Earth.
- Many of the 52 companies are initially focusing on wireless energy to power satellites or also terrestrially to create a wireless energy grid.
- Many startups are also initially focused on providing wireless power on the Moon.
- The furthest along commercial entities, in terms of funding, concept and hardware, in alphabetical order, seem to be Airbus, Emrod, Solaren, Space Solar, Overview Energy, Virtus Solis.

One key moment in the next two years may be the ESA Member States decision on whether and how to continue the development of space solar power. First commercial technology demonstrations in space will be also very notable.

The aim is to repeat this study in about every two years, but the online database and figures will be updated several times per year.

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