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REVIEW ARTICLE

A comprehensive review on space solar power satellite: an idiosyncratic approach

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Abstract
Space solar power satellite (SSPS) is a prodigious energy system that collects and converts solar power to electric power in space, and then transmits the electric power to Earth wirelessly. The main principle of this system is to supply constant solar energy by placing collectors in geo-synchronous orbit and collecting it on an Earth-based receiver, known as a rectenna. This system can overcome serious drawbacks, especially the pseudo-random intermittent capacity factor of ground-based solar power or photovoltaic systems and modules. This paper discusses some old and new concepts of solar power satellite designs and the effects of various parameters on the efficiency of collecting medium, transmission media, and receivers' area. We evaluated and reviewed the three major components of the space-based satellite that have a hand in affecting the overall efficiency of the system, which are (1) collection unit, (2) power transmission unit, and (3) the receiving unit. This paper reviews the system as a whole, as proposed in the last three decades. Many of the microwave-based SSPS models that were proposed so far are based on solar concentrators. The required launch mass and system cost could be significantly reduced by using solar concentration and hence higher efficiency can be achieved. SSPS requires new microwave technology to achieve a high power conversion efficiency of over 80% and extremely accurate beam control from the 2 km phased array transmitting antenna. Such specifications are extremely demanding and therefore significant effort is required for proper research and development. Under this technology roadmap, current research and development lead to the beginning of the new SSPS era in the coming decades.

Keywords Solar energy · Space solar · Renewable energy · Sustainable

Introduction

Non-renewable energy sources have been our energy foundation for two out of three Industrial Revolutions. Since then, industrialization has been a direct cause for exploitation of non-renewable energy sources. A survey conducted on consumption of Earth's oil reserves revealed appalling facts; if we keep consuming oil at the current rate, Earth's oil wells might dry up within the next 65 years (Chandrakanth et al., 2018). This increasing use of non-renewable energy can eventually require us to find and develop better renewable alternatives. Continuous production of atmospheric pollutants from industries and manufacturing units by developing countries and weak, inconsequential, efforts to counter carbon-based fuels with energy from renewable energy sources, especially by developed nations, has resulted in extreme climate changes and has pushed human life to an unwanted situation.

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In addition, continuous ejection of chlorofluorocarbons (CFCs) and halons like CCL_2F, HCFC-22, CCl_4 etc. from refrigerants, aircraft halon, aerosol sprays, and industries which conduct chemical reactions that break down the ozone molecules leading to gradual thinning of the ozone layer, and ultimately reducing ozone's ultraviolet radiation-absorbing capacity. However, these CFC refrigerants are being replaced with non-ozone-destroying CFCs and the major research and development efforts are centered chiefly on reducing the CO2 or methane emissions into the atmosphere.

This ceaselessly growing demand for exhaustible energy sources seems like a primary concern. Thus, the limited sources of fossil fuels and the need to reduce greenhouse gas emissions, have made renewable resources an attractive option in world economies, so to overcome this challenge of controlled hydrocarbon deposits, it is recommended to use renewable energy sources for our primary energy sources.

In order to reduce human effects on the climate system, the United Nations Framework Convention on Climate Change stated that by 2050 humans must produce clean energy equivalent to the total energy produced by every known energy source today (Reddy et al., 2015). The need for renewable and clean energy sources to replace the limited and carbon-emitting energy sources has been recommended by humans for a long-time now. This bountiful energy is naturally restored on a human timescale, such as wind, sunlight, tides, waves, rain and geothermal heat.

The sun is the brightest and purest source of electromagnetic energy in the solar system. It is the only available nuclear fusion reactor. The sun has lighted and heated Earth since its creation, which mankind has learned to convert to many other usable forms. Solar energy, though with its high technology cost and complexities in set-up, has proved to be a reliable source for many applications. Solar radiation, with its limitless, but pseudo-random intermittent supply, has a very small conversion ratio, only 11 to 15% is being converted into usable electricity. The main constraints being its pseudo-random intermittent nature, low efficiency, effect of external conditions and energy loss due to atmosphere and weather. The solar industry is a 40 billion dollar a year market, which produces less than $1/10^{th}$ of 1% of the energy we currently use. To increase this supply-usage ratio, it is more beneficial to collect solar radiation high above the atmosphere.

A space-based solar power system would collect solar power in outer space using photovoltaics and transmit it back to Earth using either a microwave or laser beam. This concept was first described by (Dr. Peter Glaser, 22 November 1968 and 1992) and has been studied rigorously by many space agencies and individuals. Collecting solar radiation in space in geostationary orbit has the following advantages:

- longer collection period because there is no night in geosynchronous orbit. A satellite orbiting in geostationary orbit receives solar radiation 24 h each day,
- higher collection rate because the intensity of solar radiations is higher; the solar intensity in orbit is approximately 144% of the maximum attainable intensity on Earth's surface with zero atmospheric diffusion
- a natural capacity factor of 99.3%
- Moreover, due to continuous solar supply there would be no reason to store the energy for later use making it a sustainable alternative for ground based solar power system.
- SBSP is an attractive concept seeking large-scale solutions to anthropogenic climate change or fossil fuel depletion.

The basic elements of a space based solar power system are the rocket-launched payload(s), solar photovoltaic receiver and energy collection either through reflectors or inflatable mirrors, conversion to microwave or laser for transmission to Earth based collectors for inversion and input to a Transmission and Distribution (T&D) grid.

Solar power satellites (SPS), as Peter Glaser termed these, are an elegant solution to the challenge of providing clean, reliable, unlimited electric energy for humanity, while generating no CO_2 or using any water: a large platform, positioned in space in a high Earth orbit, continuously collecting, beaming using Wireless Power Transmission (WPT) to transmit the energy to rectenna(s) (W. C. Brown, 1980, 1984 and 1991) and converting the energy into electricity for Earth.

The SBSP concept can be classified in many ways. Major classifications include the amount of gross power generated by each satellite, the mass to be lifted into orbit, the cost of the satellite (payload) delivery to orbit, the amount of energy collected and conversion efficiency, how it is brought together aboard the satellite, and the challenges and efficiency of its transmission to the rectenna(s). Minor classifications involve spacecraft design, structural materials, stabilization and deployment. Initially the system is launched to geostationary orbit for efficient solar input, solar radiations are then collected in several ways (1) collecting through solar photovoltaic or, (2) using reflectors or inflatable mirrors which focuses solar radiations on large solar panels. The solar energy absorbed is then converted to either laser or microwave depending on its application, most is converted to microwave which is then wirelessly transmitted to the Earth at the 2.45 GHz industrial microwave band (Gavan and Tapuchi 2010). This microwave beam aimed at a particular spot is then received by the large Earth-based receiving antenna known as "rectenna" which converts the microwaves to usable electrical energy. Some part of the energy received could be converted to laser and used in the removal of chlorofluorocarbons from the troposphere

(Stix, 1993). In spite of its technological feasibility, SBSP has many obstacles such as the cost, wireless transmission efficiency, economic viability, environmental impact, safety, societal desirability, and international acceptability. These factors related to non-ionizing electromagnetic radiation in the microwave band have long have been researched during the long history of microwave transmission from and to cell towers, FM, radio, TV, and microwave data relay (communications) antennas and towers, personal cell phones, microwave ovens, etc. (Osepchuk 1996, and OSHA Standards, USA—all available online since February 1999). They are well understood and regulated based on these many microwave standards. Microwaves are non-ionizing radiation, which does not break cell walls or destroy molecular bonds. *Ionizing* radiation frequencies, such as X-ray, always does break cell walls and destroy molecular bonds. Notably, the human body depends on natural ultra-violet frequencies to manufacture vitamin D.

Space solar collector

There are various ways through which solar radiations can be collected in outer space at heights of 400 km, a Low Earth Orbit (LEO), or higher, notably geo-synchronous orbit, where a satellite is continuously over a single longitude, making it ideal for beaming to a single rectenna(s) at that longitude.

According to (Mbunwe et al. 2020), the basic description of SPS can be adapted to two different architectures:

- *GEO-based solar power architecture*: the placement of the satellite can be in GEO, LEO or MEO. In GEO, the satellite appears to be stationary because the orbital period of the satellite round the Earth corresponds to the speed of the Earth's rotation. Hence, only less than 1% of its total time is spent in shadow due to its position in accordance with the Earth. On the other hand, if the satellite is placed in LEO, the range is minimized and the size as well as the weight of the transmitting antenna is reduced. However, these satellites spend much of their time in the shadow as they orbit the Earth, resulting in reduced productivity.
- *Lunar solar power architecture*: Here, the beam forming and the power collector equipment are mounted on the moon surface, which ultimately results in inconsistent power generation due to the 14-day lunar night.

Some of the earlier proposed SPS collector concepts as provided below:

Integrated symmetrical concentrator—A number of optical reflectors concentrate the sunlight on a focal point of the collector (Fig. 1).

According to (Belvin 2010): In the late 1990's (Mankins, 1997), NASA developed a new SPS concept based on optical concentrators. The Integrated Symmetrical Concentrator (ISC) concept utilizes thin film optics to concentrate the solar radiation and thereby reduces the photo-voltaic array size. More recently the National Security Space Office

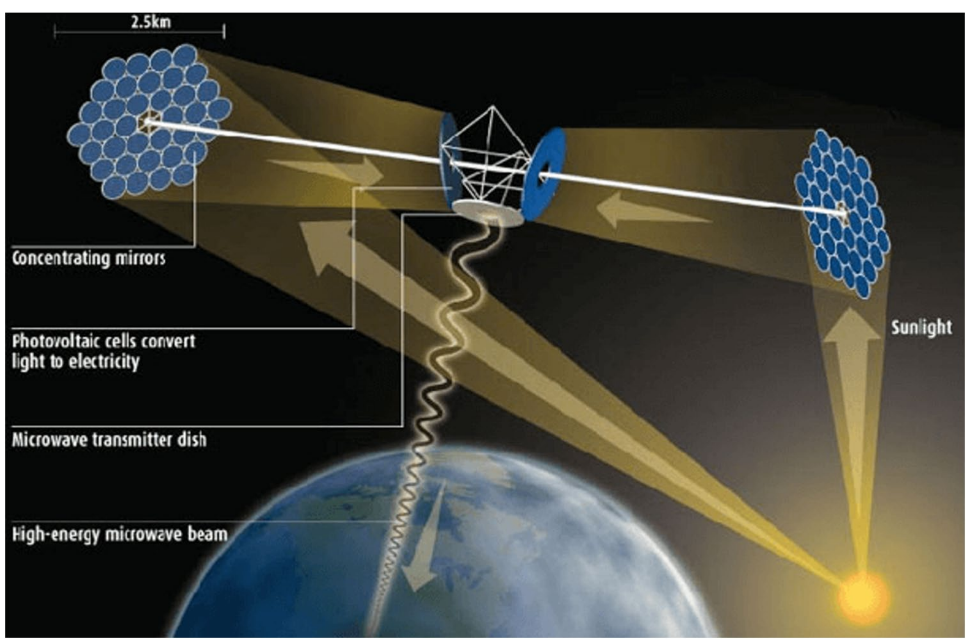


Fig. 1 Integrated solar concentrator (Belvin 2010)

(NSSO) studied the use of Space-Based Solar Power. As shown in Fig. 1, the NSSO study also adopted the symmetrical concentrator SPS concept.

The main models for SPS are as follows:

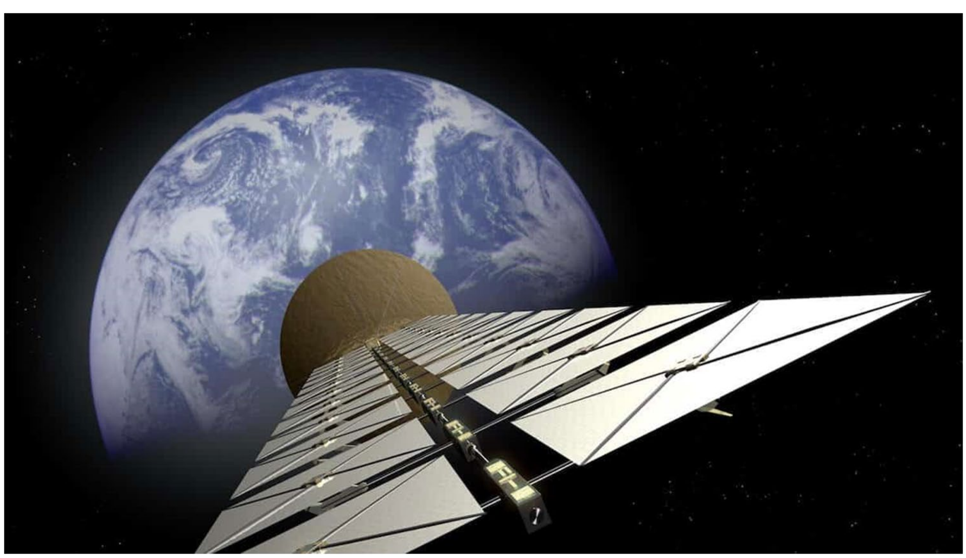
- Solar cells—This model consists of an array of solar discs covering a large area which collects solar radiation in high amounts which is then reflected to a single photovoltaic blanket, at greater solar intensity.
- Photovoltaic blanket—A large flat photovoltaic collector collecting solar radiation directly from the sun. Some design decisions include photovoltaic material efficiency from heat and the sun's ionizing radiation spectra and weather, and maintainability.
- Power generation with the help of mirrors—This model consists of two mirrors flying in the space which reflects solar radiation onto the photovoltaic panels. This model has an advantage of receiving solar energy 24 h a day.
- Solar dynamic—Some designs concentrate solar energy with the help of reflectors onto thermal boilers and turbines.

Mankins, 2008 evaluated a new design concept in NASA's Fresh Look space solar power study. The main principle of this "fresh study" was to determine whether the SSP concept is cost efficient and whether the cost decreases by applying some new methods. He introduced the sun tower concept which was considered to be an efficient alternative to 1979 SPS Reference Concept. The Sun Tower concept was introduced to overcome the drawback of large solar photovoltaic used in reference models. The Sun Tower SPS is described as a modular, gravity-gradient stabilized gadget concept in which power is generated in a sequence of equal superior photovoltaic (PV) arrays alongside a power-transmitting "spine" which conveys the power generated to a nadir-pointing phased array at the base of the "tower" (Fig. 2).

Sasaki et al., 2006 evaluated a new concept of solar power satellite updating the problem faced in the 1980 NASA Reference model. The main aim of this concept was to overcome the drawback of huge heavy rotary parts carrying many amperes and Gigawatts faced by the NASA Reference model. The authors reviewed a tethered model which was first developed by a study team organized by Institute for Unmanned Space Experiment Free Flyer (USEF) (Fig. 3). The main technologies required for this concept are the deployment of the long tether of 10 km scale and the large panel in orbit. The authors investigated tethered (SPS) which is a power generated panel slung by multiple wires from a bus system above the panel. They examined various advantages over the reference model like automatic attitude maneuvering, static structure, equivalent power generation module for low mass production, and wireless power interface between the modules. They concluded that despite its advantages over the reference model there are certain drawbacks including lack of sun-pointing capability for constant power generation.

D. Sato et al. 2017 evaluated the PV to microwave converting Tethered-SPS hybrid panel. The hybrid panel was essentially named as such, because it converted solar energy into direct current (DC) by solar cells, and then the DC is converted into microwave by DC-RF convertors which are all integrated into the same module. Moreover, the microwave which is transmitted by phased array antenna, is also integrated into that module. Through experiment and simulation, the temperature variation and the thermal resistance as well as deformation of the antenna were measured. This concept of the Tethered-SPS was proposed first by Japan Aerospace Exploration Agency (JAXA) to tackle the problem of complicated and challenging technologies required for the attitude adjustment of

Fig. 2 Sun tower



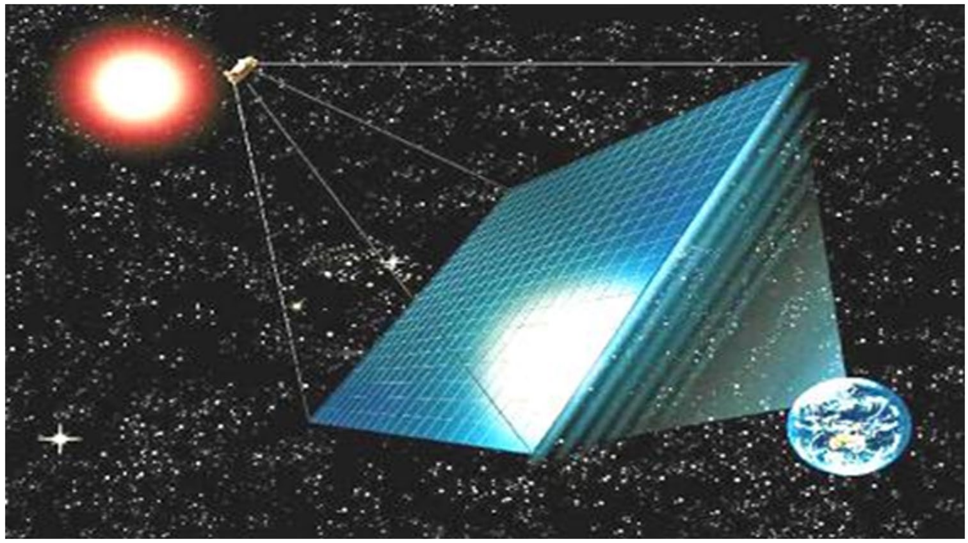


Fig. 3 Tethered SSPS

very-large-scale solar panel arrays and/or concentrator mirrors. Figure 4 shows a conceptual image of the Tethered-SPS along with the target efficiencies. Due to the absence of sun-tracking and concentrator features, the capacity factor drops to around 60%. In this paper, the authors have updated the modeling and extended the discussion to thermal deformation of the designed panel with respect to the same authors' last paper, (D. Sato et al., 2015). The results showed that the power amplifier temperature was 69 °C below its permissible range, which led to the design and fabrication of Spectrally Selective Coating (SSC) for the solar cell surface. Application of it significantly raised the temperature, indicating its promising future potential for the temperature control of the hybrid panel. The authors concluded with some future research recommendations, giving examples such as further optimization of the coating, a power amplifier that works at very low temperatures, design optimizations for long-term working etc.

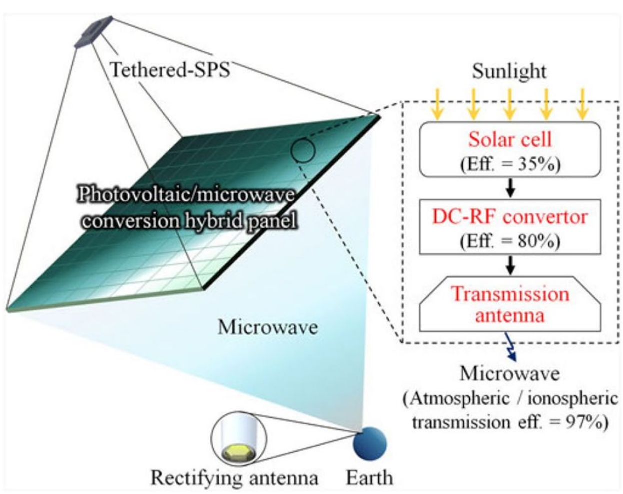


Fig. 4 Conceptual image of the Tethered-SPS and the targeted efficiencies

Seboldt et al. 2001 evaluated a new concept for collection of solar energy in geo-synchronous orbit known as sail tower concept. The main principle of the sail tower was to reduce overall cost and to have a light-weight orbital system. Sail tower consists of an array of solar sails; solar sails are large light-weight reflecting structures which use the pressure of solar photons for propulsion (Fig. 5). The "European Sail Tower SPS" is dependent on an actively propelled plan, utilizing light-weight, self-deployable and modular segments from solar sailing technology. The authors examined various modules and components of the sail tower and concluded that compared to an earlier plan concept the new approach, light-weight deployable structures, can possibly decrease mass and, consequently, the expenses of future SPS frameworks. But the technological demands and operational vulnerabilities are as yet enormous. In general, the allure of SPS is highly dependent on future launch costs, as well as the rate at which maturing microwave control transmission technologies and huge deployable structures become economically feasible and accessible.

Jaffe et al. 2014 evaluated the Modular Symmetrical Concentrator (MSC) architecture which was coined to overcome the limitations of the basic solar power system-which were mainly high cost and heavy launch mass among others. This work seeks to address and minimize the gap between the costs of deploying an operational system by the small amount of actual hardware development. Modular symmetrical concentrator prevents the need for a potentially fault-prone, large, conductive rotating joint and reduces the cabling mass compared to historical reference concepts. Using modular elements offers economical possibilities through mass production. Employing solar concentration may reduce the required launch mass and thereby reduce the cost of the system, but it increases the severity of the thermal challenges to photovoltaic efficiency. This work examines the key element of

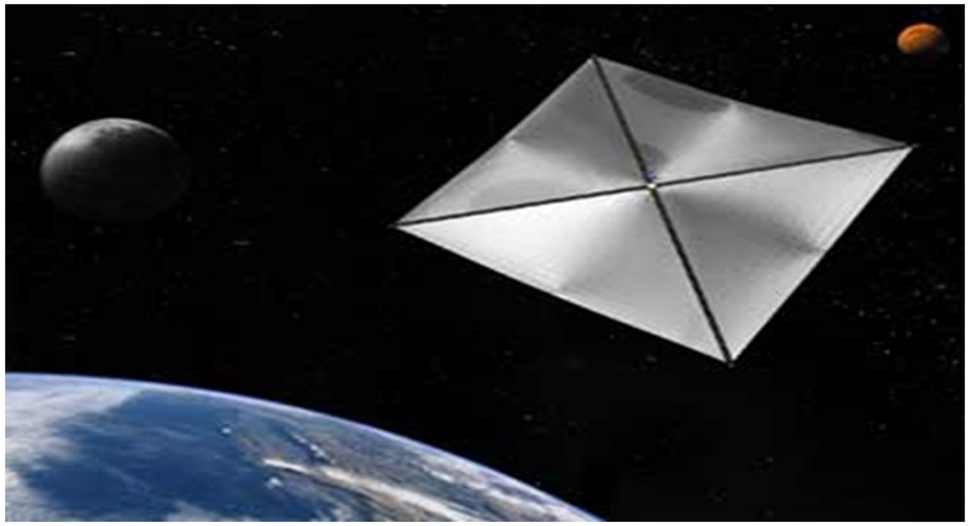


Fig. 5 Sail tower

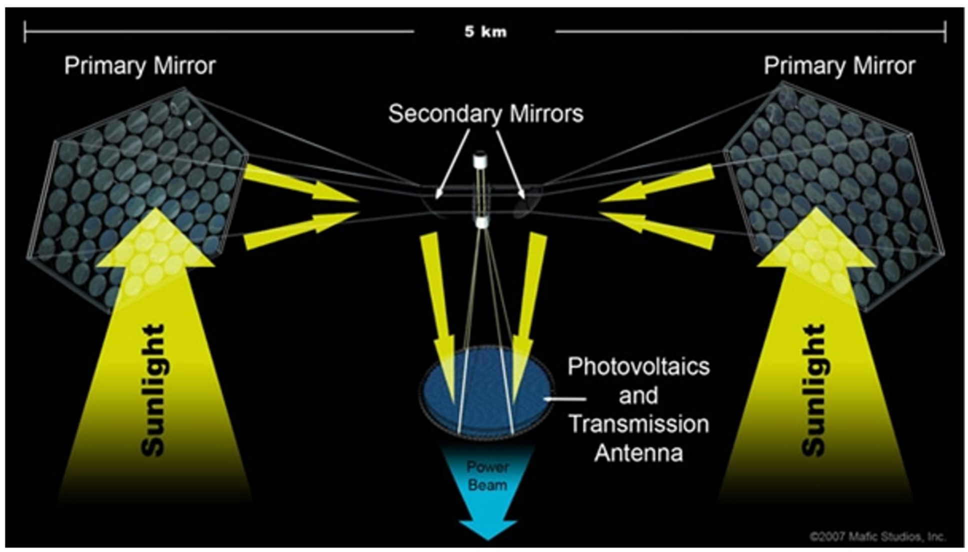


Fig. 6 Modular solar concentrator

modular concentrator "sandwich module" (Fig. 6). In this module, he identifies the maintenance of the solid state amplifiers' low junction temperatures used in a sandwich approach as a key point in ensuring permissible operating lifetime results. The efficiency of the solid state amplifier plays an important role in deciding the amount of heat that must be dissipated, as does the efficiency of the adjoining solar cell plate. This paper summarizes selected highlights from our past year research endeavors to develop designs, perform analysis, and manufacture and test prototypes of sandwich modules for space solar power. Prospective work will continue to design and develop the remaining prototype layers and test the completed components under space-like situations. This research leads to an intellectual basis for informing debates on the technological and economic sustainability of a prolific class of space solar power systems.

(Yang et al. 2016) carried out an evaluation of a novel SSPS design project named OMEGA. The main segment of the proposed GEO-based SSPS consists of four main components such as spherical solar collector, photovoltaic hyperboloid (PV) cell array, Power Management and Distribution (PMAD) and microwave transmitter antenna (Fig. 7). This concept has some technological innovations over previous concepts, such as no need for integral main reflector adjustment, low thermal control demand, wired power transfer from PV array to short distance transmitting receiver, and low-mass connection structure between primary reflector and transmitting receiver. The SSPS-OMEGA project was investigated in a conceptual study level. The manuscript examines both principles of optics, structure configuration, wired power transfer and wireless transmission. They observed that the proposed design theory decreases the power consumption required for maneuvers, has low fluctuation with the local time and the transmitting antenna is wired via long span cables to the main reflector,

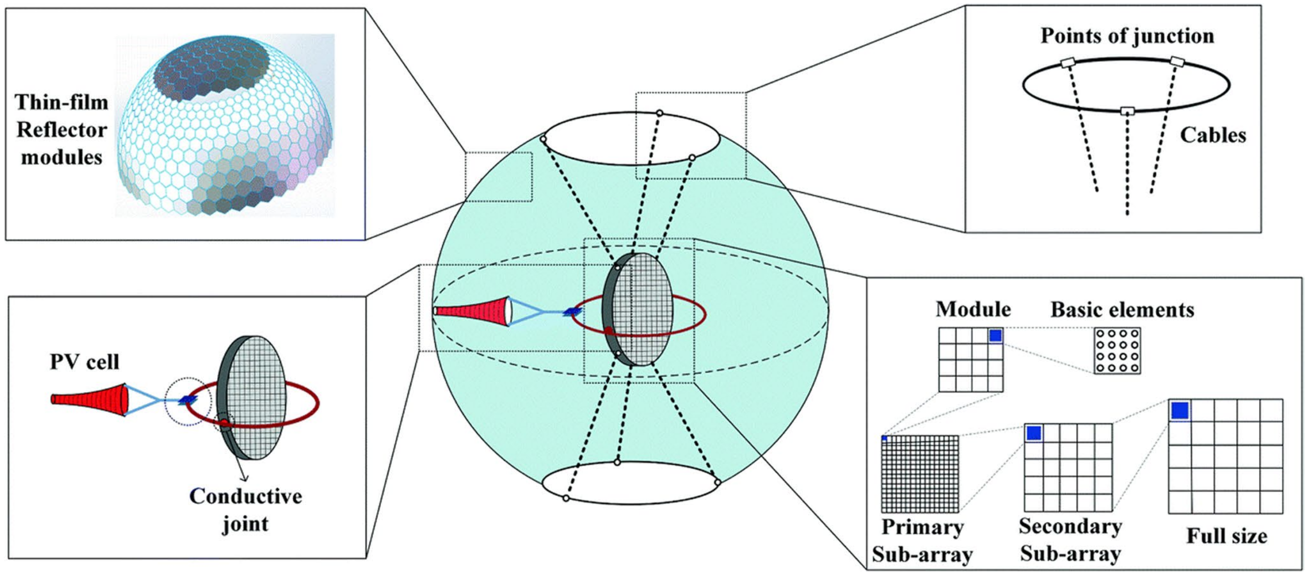


Fig. 7 OMEGA SSPS

which could reduce the connecting mechanism mass. This study's findings have substantial reference value. However, because of the low maturity for key technologies and high cost, the implementation of this elegant concept is far from complete. In addition to this, other key points should be discussed in depth as a qualitative analysis. Further research must therefore be carried out to enable the OMEGA concept.

Li et al., 2017 evaluated some new concept of space solar satellite aiming at the design structure of the collectors. They introduced various models of microwave based space solar power systems including the designs proposed by NASA and ESA. They further classified collectors into two types, solar collection through solar concentrators or directly through photovoltaics. The main aim of this research was to increase the efficiency of the solar collectors by inventing new designs to overcome the drawback of complex adjustment maneuvers to be made to redirect the incident sunlight. So they proposed the OMEGA SSPS concept, which is a spherical condenser made of Ɛ-near-zero (ENZ) metamaterial designed for solar based vitality determination. By utilizing the refractive property of ENZ metamaterial, incident light is refracted on the focal point of the condenser. This refractive property of ENZ helps to convert oblique incidence to normal incidence. A hemispherical PV array is used to gather and convert the typical daylight frequency to DC control. This paper revealed a conceptual study of OMEGA SSPS and pointed out some advantages over conventional designs like constant solar energy consumption, high transmission efficiency, and non-moving condenser which in turn decreases efforts and cost to conduct complex maneuvers. However, there are still some problems relating to temperature distribution over a PV array which is still at its initial stage.

Space solar power transmission

Electricity is transmitted through conducting wires on ground as transmission is within reachable range, while in space when electricity is to be transmitted from geo-synchronous orbit, wires are not feasible, so it is important to transmit power wirelessly. Initially, solar energy collected through photovoltaic panels is converted to a suitable source of transmission. There are two ways of wireless transmission over a distance of 36,000 km.

Laser beam—The solar energy is converted to a laser in orbit itself. Transmission at high power is very important for efficiency, high power is obtained at low voltage. Laser beam operates at low voltage which helps in transmitting power over a large distance. Also due to its low divergence angle transmission over a long distance like from space to Earth seems feasible. The main disadvantage is that it is susceptible to atmosphere, moreover it requires high accuracy during beaming.

Microwave beam—Solar energy collected is converted to microwave. These wavelengths can make narrow focused beam transmissions which helps in planning how to use smaller sized rectennas. Also due to its beam width and frequency, it has a large power-carrying capacity. The power density of these beams at the rectenna is lower than cell phone transmission power density at the user's ear, for example. Power density under the rectenna would be extremely low, which would enable commercial farming below these and making ownership of the land under the rectenna by the rectenna owner unnecessary—very similar to wind mill operators who simply pay air rights to farmers. The main disadvantage of microwave power transmission is that they are limited to line of sight propagation, they cannot pass through any hill or mountain with microwaves.

Radio wave transmission—The main advantage of radio frequency wave transmission over others is its path of transmission. The radio waves can travel through walls and through an entire building.

A novel SPS idea in which a laser power beam transmits power from geosynchronous orbit to the upper atmosphere where it is retrieved and transported through the atmosphere by link or microwave was evaluated by (Schafer and Gray, 2012). The aim was to deliver an underlying plan that is adaptable and can be executed utilizing existing or near-future technology requiring negligible capital speculation before conveying electrical capacity to buyers. Where more conventional SPS designs require Manhattan Project level investment and speculation before conveying a solitary watt, the little fastened aerostat demonstrator proposed toward the end of the paper conveyed power even without illumination by the laser control bar. The authors also examined laser emitting SPS which uses thin-film solar cells with light-weight optical fibers for power distribution. They introduced the laser power transmission framework resulting in a highly intelligent stage conjugator arrangement. At a subsequent stage they suggested testing a proposed laser framework with an automatic tracking system ideally by utilizing fiber. The authors concluded that a microwave power link appears best for the long term, while a cable system is most suitable for a near term low cost demonstration.

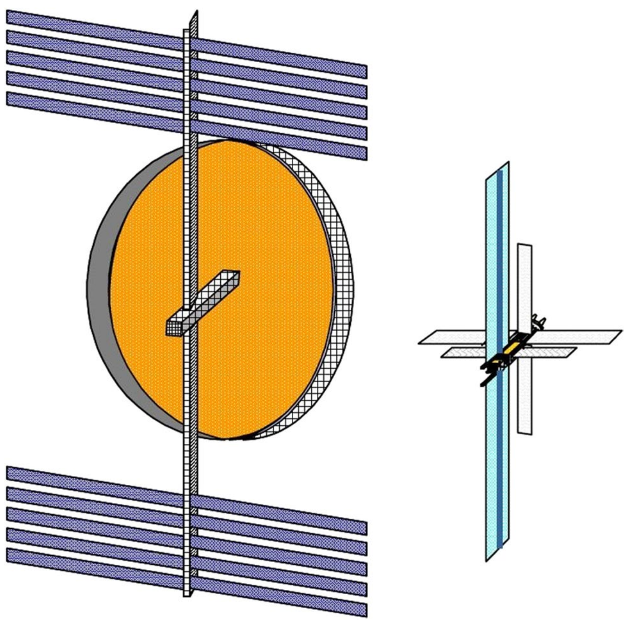


Fig. 8 (**a**) RF-based SPS and (**b**) laser-based SPS

Henderson, 1980 proposed a hybrid SPS concept in which solar radiations are collected in geosynchronous orbit and transmitted by a concentrated laser beam to a receiver located at an altitude of approximately 30 km mounted on a 2.6-km diameter rigid balloon. The collected power is converted to microwave beam and the heat loss in this energy conversion is used to power balloon platform which could perform other functions related to Earth observation and communications. The main principle was to transmit power in the form of a laser which is a more efficient way of transmission compared to the US Reference Microwave SPS system. The author concluded that the significant advancements in high power lasers created within the last 10 years, and predictions for future optical device performance give confidence that the SPS laser power transmission system may be a technological feasibility within the timescale of introduction of recent energy sources. However, there are some problems related to its feasibility like economic, technological and social acceptability of laser beaming. Hence, he quoted that with the utilization of rising technology the laser power transmission system suggested could also be as economical as the current Photovoltaic Microwave System, even though it potentially answers several criticisms of the relevancy of the SPS system to European use, it remains to be seen whether or not the system is as possible economically and logistically.

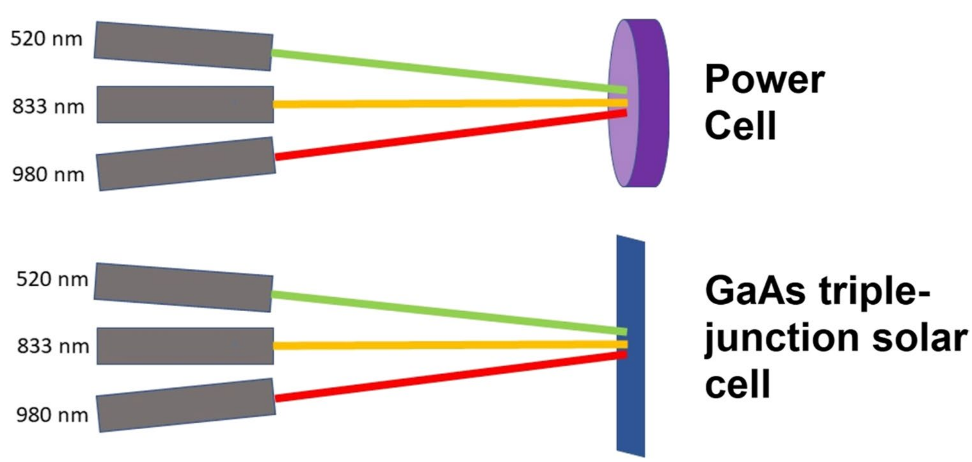


Fig. 9 Illustration of the experimental setup

Some of the other publications have been tabulated as follows:

Author	Objective/Aim	Experimentation/Calculation	Results/observation	Conclusion
(Sasaki et al., 2011)	Techniques required for power transmission through microwave beam or radio beam	The microwave beam at maximum power was transmitted to the Earth for 16 s directed by the transmitter signal from the receiving site when the experiment device flew over the ground station	Evolutionary microwave technologies are needed for a high power conversion efficiency of more than 80% from/to DC and a highly accurate beam control with 10 μrad accuracy	While the technologies needed are quite difficult, continued research activities along with the expected roadmap will lead to the construction of the new SPS generation in the 2030s
(Sasaki et al., 2013)	Examined various factors that affect efficiency and power level like frequency band and rectenna configuration	Compared microwave and laser power transmission based on its frequency, ionospheric transmission and conversion efficiency	Microwave power transmission is more beneficial in every sector	The SPS requires new microwave technologies for accomplishing a powerful conversion efficiency of over 80% from microwave to DC and a high precision beam control with 10 μrad precision from the 2 km^2 exhibit array antenna
(Shinohara, 2013)	Evaluated beam control technologies for microwave power transmission The main research aim is to provide an overview of several fielded microwave power transmission experiments using phased arrays in Japan and to provide information on the efficiency dependency on various phases using MPT since the 1990s	-	(1) In order to realize a highly efficient MPT at a distance of 36,000 km, using a frequency of 2.45 or 5.8 GHz, the number of antenna elements for SPS applications would need to be greater by six to seven orders of magnitude than currently established projects (2) To minimize the launch costs for the SPS systems, the weight of the phased array would need to be lower by two to three orders of magnitude	Cost is perhaps the most important variable for MPT to be ubiquitous using phased array MPT. Apart from cost, the new technologies, such as wideband gap semiconductors, will propel phased-array technologies forward
(Cougnet et al., 2004) (Refer Fig. 8)	The objective is provide permanent power to the Mars surface rover which is assumed to be operational in a 400 km diameter and would require 500 W while operating and 50 W while in resting mode. The main research aim is to provide solutions for the selection of a transmission method to a rover on Mars or directly to the Mars surface as well as that of the moon	-	On a Mars base, RF power transmission is preferred because the size of the receiver is not an important factor and the base would need power during the dust storms as well; which laser beam is incapable of doing	(1) In the case of RF: the technology for the signal generator and the rectenna could be improved for 35 GHz due to the efficiency and mass In the case of laser systems: new technologies like solar pumped lasers or improvements in fiber lasers are required for the same reasons (2) Better solar receiver technologies are essential to reduce SPS size
(CDR Sanders et al., 2020) (Refer Fig. 9)	A larger satellite beams power to the smaller ones with three lasers of different wavelengths	Assessed the design for a polychromatic laser system to transmit power to a space-grade solar cell and optimize its spectral response with the help of three different laser wavelengths The setup (Fig. 10) was that the lasers are pointed on the same solar cell and the peak values of power from each laser is observed	In comparison to a single-wavelength laser, the multi beams outputting the same amount of power generated 38% more power at the target solar panel. Whereas, the same three beams outputting with optimized amounts of differing power generated 85% more power at the target solar panel. These optimized values for highest efficiency of each of the lasers were 5% for 980 nm, 45% for 833 nm and 50% for 520 nm laser	An illuminated, orbiting satellite can beam power to other satellites or to ground assets. Beam wavelength matching is expected to increase the solar panel efficiency to over 50% Main advantage of this method is that the target asset can utilize the existing solar panels to receive power, in addition to sunlight, eliminating a requirement for specialized power receivers
(Oliveri et al., 2011)	Calculated and optimized the weights of the planar arrays for Wireless Power Transmission The main aim of the authors here was to maximize the ratio of the microwave energy which actually impinges on the rectenna to the total transmitted power. This is called Beam Collection Efficiency (BCE)	Used an analytical method which formulates the synthesis process as a generalized eigenvalue problem. The methodology can be applied for any geometry of a transmitter array irrespective of the rectenna shape	The results of the procedure were carried out through a Jacobi–Davidson method applied to the solution of the generalized eigenvalue problem	They concluded that this method achieved high BCE values and numerical efficiency by validating it numerically

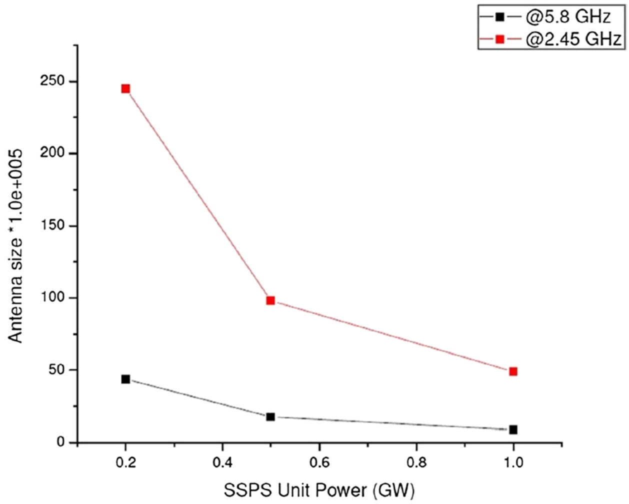


Fig. 10 Antenna size (m^2) variation with different GW power units

Chaudhary et al., 2018 evaluated the microwave transmission frequency from a satellite solar power station by taking four cases. The main objective was size estimation for system components as well as optimization for the selected 10-GW base load power supply. This was achieved by applying an increased number of fractional power unit modules and assembling them for constant base load power supply. This led to economic advantages and most importantly the reduction in antenna size. The results showed that a changed beam efficiency directly affected the receiving antenna size. It was concluded that a 2.5 GW unit with 90% beam collection efficiency of the transmitting antenna will provide the optimized size. Moreover, for high beam collection efficiency, a larger antenna surface is required. Figure 10 also shows a relatively lower size requirement at 5.8 GHz for the different cases that were studied in the paper mentioned. Hence, achieving increased beam efficiency even at a lower power unit is attainable. The final conclusions were that power transfer at 5.8 GHz frequency is smaller in size than that at 2.45 GHz in SSPS. Nonetheless, this could only be valid up to 1 GW units. The design of high power antenna phased array is found to be impractical if unit modules of more than 1 GW are consider.

Solar receiver

The microwave receiver is considered the most important component of the space solar power system as its efficiency is a critical part the systems overall efficiency. Energy collected by photovoltaic collectors is converted to electromagnetic energy and beamed by the satellite in space. Since a storage system is not needed, at a suitable frequency it is directly transmitted through the atmosphere to the rectifying antenna or "rectenna" on Earth. (W. C. Brown, 1980, 1984 and 1991).

The *Rectenna* is a type of receiving antenna which is used for converting electromagnetic energy into direct current (DC) electricity. It is spread over a large area of several square kilometers. It consists of a mesh array of dipole antennas connected to diodes to convert the radio frequency energy to DC voltage, which inverters then convert to regular AC electricity and wired to homes, factories, etc.

One rectenna element rectifies only a few, therefore an array of rectenna is used for high power collection which in turn requires a large area. The rectenna array is not connected in microwave phase but in DC phase either through series or parallel connection. Research has proven that total power decrease is higher in series connection compared to parallel connection, thus parallel connection is more efficient. The total area covered by the rectenna is decided according to Fresnel's area concept.

Dickinson, 1976 evaluated the performance of a high-power, 2.388 GHz receiving array in wireless power transmission over 1.54 km. The main aim of this work was to determine the performance of a microwave power receiving array through an experiment. The receiving-converting subsystem array was installed about halfway up a 30-m tower divided by a 1.54-km tilt range at an inclination of 7° from the Venus station's 26-m parabolic antenna at Goldstone near Barstow, California. In addition to the standard power output versus power input or performance measurements, a series of tests were carried out to determine the efficiency of the receiving-converting subsystem array under different conditions to provide non-standard operating characteristics and to define flaws in the system. Thus, with respect to DC load, RF frequency, polarization, power density level, distribution and ground spacing, a highly effective, rather sensitive, non-varying RF to DC converter was characterized over certain distances. The rectenna array was successfully used to transmit > 30 kW of power over a range of 1.54 km with over 80% collection-conversion efficiency. However, when power is transmitted over vast distances, cost as well as losses increase, so future rectenna studies should be include reducing the cost of production, enhancing capacity range, as well as improving efficiency.

A review of array design techniques for long-range WPT was presented by Massa et al., 2013 paper. The recent progress and innovative solutions regarding the design of the receiver layout (a problem of wave collection) were addressed and some of the recent trends and potential future boundaries of this research area were assessed. This review observed that the highly efficient end-to-end WPT transmission requires more specifically an integrated design strategy,

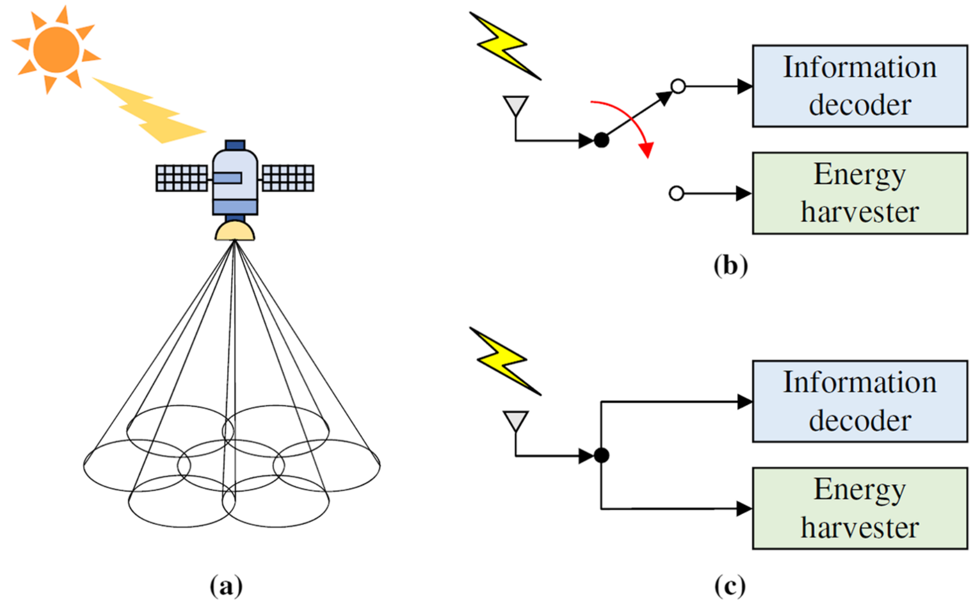


Fig. 11 Illustration of the SWIPT technique in the STIN using (a) a multi-beam SPS; (b) time switching architecture; (c) power splitting architecture

and appropriate techniques to optimize the effectiveness of retrodirective beam focusing, these strategies are of primary importance for ameliorating the safety and efficiency of WPT systems. While with regard to WPT receiving configurations, the specification of suitable array architectures and RF-to-DC conversion schemes portrays a critical aspect of the design process, and various tradeoffs are possibly based on the target configuration, expense, and desired efficiency. By considering RF summation architectures, a rectenna array with DC power having high efficiency is obtained. These systems, however, also on the receiver side need to develop and implement monitoring techniques. In addition, the architecture and manufacturing of single rectennas and their optimum geometric displacement are still a large area of research that needs to be carefully studied.

For the application of microwave power transmission, the diode frequencies are 2.45 and 35 GHz and the use of a frequency sensitive surfaces were investigated by (McSpadden et al., 1992). A procedure was developed to describe experimentally a packed GaAs-Schottky barrier diode by placing it into a microstrip test mount. A specific signal test method was introduced for the diode's non-linear equivalent circuit variables. The system evaluated the parameters of scattering of the diode at various bias stages.

A large signal analysis was also designed using the same test mount to calculate the power conversion efficiency from microwave to dc and to evaluate the diode's de-embedded system impedance. Thus the maximum theoretical output was estimated as 91% and when performed at an input power level of 1.2 Watts the maximum observed efficiency was 85%. Based on the computer examination, a 35-GHz rectenna was also developed. The rectenna was constructed using a field antenna with a microstrip and a mixer diode with Kuband. At 120 mW input power, the estimated output was 29%. At a small rectenna array nearly 10 dB of exhaustion occurred at 4.9 GHz and the conversion efficiency decreased by less than 1%. Thus, this work calculated the efficiency under small and large signal conditions.

McSpadden and Mankins 2002 evaluated the microwave wireless power transmission devices and the effects of different frequencies on the efficiency of DC to RF conversion. They also examined ground based rectifying antennas at different frequencies of 35 GHz and 5.8 GHz and compared its efficiency with the standard 2.45 GHz rectenna's efficiency. Evaluation showed that 2.45 GHz rectenna records highest efficiency in the microwave frequency range at 91.4%. To achieve high efficiency apart

Table 1 Expected growth rate of supply and demand of energy sources

Average projected energy demand growth	Absolute change (as percent of current supply) by 2025 [in %]	Necessary growth in renewables + nuclear (percent of current supply) by 2025 [in %]	Necessary annual growth in renewables + nuclear [in %]
1%	15	22	9.3
2%	32	39	12
3%	51	58	15.6
4%	73	80	18.5
5%	98	105	20

from varying frequencies, selection of diode is the most critical component, since it is the main source of loss. Schottky barrier diodes utilizing Si and GaAs are suggested with rectification efficiency greater than 80%. So, after examining the performance of rectenna at varying diodes, frequency and filters, the immense transmission range and receiving 500 m and 7.5 km diameter apertures, the power transfer capacity approaching 36,000 km turns out to be 45%. Efficiency greater than 45% can be obtained by selecting proper diodes and measurable frequency but this study was in its initial stage and further work was desired.

It is suggested that improving an antenna's beam path will improve the Wireless power transmission system's energy efficiency. Both the directional antennas and the antenna arrays can achieve this objective. Shen et al., 2019a, b formulated an improvement to orchestrate the power design and decrease the maximum side lobe level of the planar antenna array for wireless power transmission. An Improved Chicken Swarm Optimization (ICSO) calculation was proposed to tackle the proposed advancement issue, in this way accomplishing a superior power design with lower greatest side lobe level. They also conducted simulations to substantiate the performance of the proposed ICSO algorithm for the power pattern synthesis. Thus, the main aim is to change the parameters of ICSO to achieve optimal solutions. The result shows that the effectiveness of ICSO is higher compared to various known techniques, the convergence rate and efficiency of ICSO can be improved by simulating introduced improved factors. The algorithms were tested by electromagnetic simulations and results were obtained which showed that the ICSO algorithm has best performance in an electromagnetic environment.

Some of the other publications have been tabulated as follows.

Author	Objective/Aim	Experimentation/Calculation	Results/observation	Conclusion
(Lin et al., 2020) (Refer Fig. 11)	The main objectives for this work were to minimize the deficit or excess of information transmission rate and maximizing power transmission based on two receiving architectures of terrestrial devices for information decoding and energy harvesting	Proposed a new Resource Allocation (RA) problem of a multi-beam SPS performing the technique of Simultaneous Wireless Information and Power Transmission (SWIPT) in a Space-Terrestrial Integrated Network (STIN). The major advantages of SWIPT applied in STIN with a multi-beam SPS is 6G networks and super Internet-of-Things (IoT). The problem is solved by using three different Artificial Intelligence algorithms to aid in optimizing the network resource management	The results showed that of these two receiving architectures, the Power Splitting (PS) architecture was better in overall performance than the Time Switching (TS) architecture Also, the Improved Harmony Search (IHS) algorithm was able to maximize the power transmission without affecting the information transmission	The author expects hybrid STIN containing GEO, MEO, LEO satellites or mobile base stations to be discussed in the future for diverse applications such as IoT and edge computing
(Zhou et al., 2013)	Evaluated different practically-viable methods for simultaneous wireless information and power transfer using Dynamic Power Splitting (DPS), in which the received signal is dynamically split into two streams with a random power ratio over time. The authors have proposed two practical receiver architectures (separated and integrated information and energy receivers) and calculated the rate-energy performance taking into account the power consumed by the circuit itself	The separated power receiver splits the signal into two signal streams in the RF band and then separately feeds them in a conventional energy receiver and information receiver. Whereas the authors propose an integrated receiver where the information decoding and energy harvesting circuits are integrated into one, leading to reduced energy cost for information decoding	The results showed that the separated receiver is superior at the low harvested energy region and the integrated receiver is better at the high harvested energy region	It is shown that the integrated receiver attains higher rate than separated receiver for small transmission distances, if a zero-net-energy consumption system is taken

Challenges and future scopes

Space based solar power systems offer the prospect of effective, environmentally friendly electrical power. It can potentially provide endless renewable energy without the problem of day-night cycles and clouds. There are challenges to be overcome. The biggest obstacle to solar power satellites was identified as the cost of putting the necessary hardware in space. (O'Neill, 1975), requiring reusable launch vehicles. The cost of placing a power satellite in a geosynchronous orbit should not exceed initial costs of $200/kg for 6.5 kg / kW, if the cost of power is to approach market levels as the design matures in rectenna (power delivery) efficiency.

This year, Elon Musk's SpaceX has reused a Falcon 9 booster ten times, a most important milestone on our journey to cis-lunar space commercialization, including SSP:

> SpaceNews - WASHINGTON — SpaceX launched a set of Starlink satellites May 9 on a Falcon 9 whose first stage was making its tenth flight, a long-awaited goal in the company's reusability efforts (Foust, 2021) With Starship, it could be 1 percent the cost of an expendable system," Musk said. "The marginal cost of launch we think could be under $1 million with 10 times the payload of Falcon 9. (Musk, 2021)

The space environment is harsh; if PV panels are used, they suffer about 8 times the deterioration they would have on Earth (except in magnetosphere-protected orbits). Also the inability to control power transmission within tiny angles of the beam, a beam of 0.002 degrees (7.2 arc seconds) is required to transmit power from geostationary orbit to the receiving antenna separated by the distance of 1 km, dictating very large kilometer-scale aperture phased-arrays in orbit. As of 2019, the most powerful existing directional wireless power transfer systems extended their half-power beam width over at least 0.9 degrees in arc. However, if these challenges were overcome with much larger system apertures, it should be remembered that it took several shuttle missions to launch the acre of panels that make up the ~ 100 kW generating capacity of the International Space Station. This capacity is priced at $10,000 an hour if we continue to expect $0.10/ kWh and no transmission losses. The factors outlined above show that space-based solar power is becoming an available solution to the energy challenges we face.

While SPS faces many obstacles, it is not as far-fetched as some might assume. Looking at the current rate of developments in the wireless transmission sector and reusable rocket industries, the space solar power concept seems to be applicable in the decade ahead. It is projected currently to be around US$ 1 per Watt of usable capacity, and would also decline with improved launch technology and larger scope. The cost of production of orbital solar power plants could also become substantially lower than that of any Earth-based power plant. Also the improvements in the conversion of radio waves to electrical waves has increased the probability in a much larger way. The potential of SBSP to provide clean, reliable power to the world 24/7 at a lower cost than any other source of energy is true. It will, of course, take years of planning, development, research and successful power delivery before an SBSP program can recover its original costs.

Jakhu et al., 2016 evaluated the political and legal limitations as well as mainly the safety risks concerned with the development, launch and operation of SPS in the future. The main objective of this paper is to identify the safety risks and analyze the damages caused by SPS specifically under international law and the domestic law of the US John Mankins, a SPS expert, summarized the challenge of SBSP as balancing between constantly transmitting energy to the Earth at a level that should be high enough to be useful and low enough so as not to cause any damage. He also stated, "The single most important policy consideration for SPS is that of WPT beam health and safety" (Mankins et al. 2011). The main determinants are the form and intensity of the energy to which living things and the environment are exposed. Lasers, due to their radiation outside of the visible range, could create hazards which are insidious for people working and living near ground stations, flying in aircraft, and possibly to bird populations. On the other hand, as stated earlier, microwaves do not damage cell walls. However, their transmission from space to Earth could cause some other problems as discussed below.

Some of the SPS-related risks and liabilities are briefly summarized by (Jakhu et al.) as following:

- Technical flaws with the design, including its capacity to produce power at expected levels and cost-effectively.
- Design flaws or problems with the location of the rectenna; for example, reflected energy could cause problems for airplanes, neighboring residences or industry, or even satellites that require a low noise environment to operate. Rectenna could have a negative ecological impact on fish or ocean life, as well as nearby wildlife.
- Transmission via laser, millimeter wave, or microwave, as well as conversion from electrical power to radio frequency and back, has a number of issues that could result in interference with other satellite systems, medical protective systems, and so on; this would necessitate operation from Low Earth Orbit (which is already very congested) and would be very difficult indeed.
- If the power transmission unit from the SPS back to Earth had a pointing accuracy problem, especially if the pointing system malfunctioned and started beaming power or radio frequency emissions at military, communications, remote sensing, navigation and time, weather sat-

ellites, and other satellites with a threat to disable them, it could result in a multi-billion dollar liability.

Wie and Roithmayr 2001 evaluated the main concepts for guiding the orbit, attitude, and structural movements of a SSPS in geosynchronous orbit. Their main focus was on a 1.2 GW "Abacus" SSPS configuration with a square solar array platform (3.2 km × 3.2 km), a microwave beam transmission antenna with 500-m diameter and an Earth-tracking reflector (500 m × 700 m). External disturbances such as solar radiation pressure, microwave radiation, gravity-gradient torque, and other orbit perturbation effects are examined by the authors in a comprehensive set of mathematical models. From the researched portion of these authors, they recommend the following research topics in the areas of dynamics and control of large flexible space platforms, to be investigated further, for the support of development of large SSPS.

- Thermal distortion and structuralThermal distortion and structural vibrations due to solar heating
- Simultaneous eccentricity and longitude control
- Attitude control during the solar eclipses
- Orbit and attitude control during assembly
- Attitude and orbit determination problem
- Reflector tracking and pointing control problem
- Microwave beam pointing analysis and simulation
- Electric propulsion systems for both orbit transfer and on-orbit control
- Backup chemical propulsion systems for attitude and orbit control

Mbunwe et al. 2020 provided the recent projections of growth rates for supply and demand of energy sources as shown in Table 1.

According to (Mbunwe et al. 2020), the key challenges for the SPS concept are in terms of high costs, emerging technology, international policy and regulations, health and safety, as well as terrorism. The aspect of terrorism comes into play as the high power microwave source with high gain antenna is usually employed in delivering intense bursts of energy which can be used as a weapon. However, the greatest obstacle in the development of the SPS is high launch costs. Consequently, a major spacecraft development project hundreds of millions of dollars, and over a lengthy period of time. Such technical challenges greatly influence the economic feasibility of SPS.

The key findings of a recent international assessment developed by the International Academy of Astronautics (IAA) Study (Mankins et al. 2011) were as follows:

1) Need for new energy technologies such as SPS
2) SPS is feasible
3) SPS will soon be economically viable
4) More research is needed to fine-tune all parts of the technology
5) Low-cost ETO transportation will make SPS commercially viable
6) Prototype testing-of-concept need to be initiated to boost technology confidence
7) Technological development is currently transient
8) Existing power networks for transmission
9) Need for regulatory and policy frameworks.

Although there are still many unknown factors involved with SBSP and its application in the coming years, one thing is certain: it will be crucial for SBSP to evolve beyond the concept phase into a new type of efficient renewable energy. Using that new phase of energy into the world would profoundly change society.

Conclusion

The current generation of solar energy has expanded due to increased demand for renewable energy. However, the current rate of solar energy extraction is able to provide energy only in small amounts to large subsidized corporations. Thus, keeping in mind the ever growing population and industrial revolution we are compelled to use a more efficient and limitless way of producing solar energy. Thus to meet the need for clean reliable renewable solar energy in the future, SSPS becomes an indispensable option. Producing limitless solar energy by collecting solar radiation in space and transmitting it to Earth can provide 24 h, 365 days per year supply. Evaluating various researches and studies has concluded that concentrating solar structures are best suited for an efficient solar collection, of all collection mediums. SSPS-OMEGA provides several benefits, it is cost-effective and has low energy consumption also the transmitting antenna is connected to the main reflector through cables, which reduces the mass of connecting mechanism. High-efficiency wireless power transmission requires an advanced design approach for both transmitting and receiving configurations. Microwave power transmission commits to this strategy and provides optimal efficiency and low power loss. Though rectenna arrays with total DC power combination are the most commonly implemented scheme, an undeniable increase in output is achieved through radio frequency architectures. However, such systems still need the development and implementation of tracking strategies on the receiver side. Despite the efforts of the last few years most issues related to WPT arrays are still at an initial stage of development, and a substantial increase in research activities in this region is intended. The main challenges concerning the overall performance of the space solar power satellite are:

- The cost of transportation: operational SBSP designs weigh up to several hundreds of tons per payload requiring huge rockets and large amounts of rocket thrust to build in the geo-synchronous orbit.
- Maintenance of the massive solar modules which includes its position in the geo orbit and manoeuvres required to keep pointing in the direction of the sun.
- Narrow carefully focused beam of microwave radio wave is necessary to reduce the size of the receiving antenna.
- The conversion efficiency which consists of solar radiation to micro/radio waves and from radio/microwave to DC. High conversion efficiency can be obtained by using different types of diodes in the rectenna and transmission at higher frequency in laser beams.
- Area of both collector and receiver—larger the area, the larger the overall cost, but it also increases its efficiency, which is why NASA's 1981 Reference design stated the system delivery breakeven point began around 5 Gigawatt delivery levels, depending also on launch cost, technology maturation and mass production learning curves. Microwave ovens, once cost $5000 each when they were first introduced, but later dropped to $50 each with similar technology maturation and mass production learning curves.

Overcoming these challenges will be increasingly better designs and will take decades to implement. However, on the cusp of true reusable space launch, combined with the highest continuous unique power available from advancements in competing SPS design models, a novel and limitless supply of low-cost, renewable baseload power may soon be in sight. A space solar power satellite is nearer than ever due to the emerging technologies such as reusable launch vehicles, carbon nanotechnology, additive manufacturing and many more. Using technologies that have begun emerging from laboratories, a satellite can be developed, deployed and made economically viable. More work is necessary to make more accurate measurements to apply the technology from the laboratory to actual space deployment and then to its logical end as an environmentally clean, limitless, reliable, renewable source of energy to fuel our future.

Abbreviations SSPS: Space solar power satellite; SPS: Solar power satellite; SBSP: Space-based solar power; SSP: Space solar power; LEO: Low Earth orbit; GEO: Geostationary Earth orbit; MEO: Medium Earth orbit; NASA: National Aeronautics and Space Administration; ESA: European Space Agency; WPT: Wireless power transmission; RF: Radio frequency; BCE: Beam collection efficiency; PV: Photovoltaic; SWIPT: Simultaneous wireless information and power transmission; STIN: Space-terrestrial integrated network; DPS: Dynamic power splitting; GHz: Giga hertz; nm: Nanometer

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Data availability All relevant data and material are presented in the main paper.

Declarations

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Consent for publication Not applicable.

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