August 2022| Volume 01 | Issue 02 | Pages 09-16

Future Energy
Open Access Journal
ISSN 2832-0328

Journal homepage: https://fupubco.com/fuen

https://doi.org/10.55670/fpll.fuen.1.2.3

Future Publishing LLC

Review

Solar power satellites: technical challenges and economic feasibility

Gerardo Antonio Urdaneta*, Christopher Meyers, Lauren Rogalski

Department of Mechanical Engineering, Arkansas Tech University, 1811 N Boulder Ave, Russellville, AR, 72801, USA

ARTICLE INFO

Article history:
Received 24 March 2022
Received in revised form
25 April 2022
Accepted 30 April 2022

Keywords:
Solar Power, Microwave Transmission, Specific Impulse, Low Earth Orbit (LEO)

*Corresponding author
Email address:
gerar4406@gmail.com

DOI: 10.55670/fpll.fuen.1.2.3

ABSTRACT

World energy consumption is constantly rising; therefore, it is essential to investigate different possibilities to produce power in the medium and long term. The sun is a clean source of power that is virtually inexhaustible. Photovoltaic (PV) power stations are used to harness this energy, but they are not completely reliable since they depend on weather patterns. To overcome this problem, large satellites with extensive solar panel surfaces can be placed in orbit. These satellites, known as Solar Power Satellites (SPS), would be positioned in geostationary orbit (GEO) thus constantly providing energy while avoiding meteorological conditions and erosive factors. These benefits make solar power station an appealing option for the energy of the future. Therefore, in this paper, the possibility and challenges of using solar-powered satellites are explored. The mechanisms regarding microwave transmission, photovoltaic collection, radiation impact, and propulsion are discussed. The advantages and disadvantages of solar-powered satellites are discussed regarding cost and practicality, and the current race between different countries to achieve this technology was examined. It was found that power could be collected with an efficiency of over 30% using gallium-arsenide photovoltaic cells. To minimize radiation effects, the use of a 100-micron transparent Pilkington Borosilicate Glass (commercially known as CMG cover glass) could be employed. For spacecraft propulsion, Hall thrusters provide the optimal combination between efficiency and thrust. Finally, the cost analysis indicates that to make the SPS viable, launch costs to GEO must be decreased by a factor of 10, solar panel efficiency must be increased to 40%, panel density must be minimized, and international cooperation must be achieved.

1. Introduction

Solar Power Satellites (SPS) are being looked at not only as sources of energy on earth but also as an incentive to reduce the size and launch costs of satellites [1]. Today's world is currently suffering from increased consumption of its resources. With such increasing demand, it is necessary to begin exploring other energy sources. There are three main reasons for this drive for new and more reliable resources, such as the fluctuation of the petroleum industry peaking, the fuel-derived greenhouse gas effect, and in general, growing global demand for energy. SPS collect the solar radiation in space and transmit it using a microwave energy beam to a receiving antenna on earth which transforms it into electricity [2]. When it comes to solar-powered satellites, there are many benefits over other traditional forms of power supply. SPS is not affected by the weather or the earth's atmosphere. This allows SPS systems to be set in the most optimal path for solar and energy absorption. On the earth's surface, the average solar power per unit area is 250 W/m^2 whereas in space is 1366 W/m^2 [3]. Unlike terrestrial solar power, solar power in space does not need to be stored anywhere in case of drastic weather. Furthermore, the space vacuum superconductor property for electromagnetic energy transmission is an important benefit over transmission systems on earth. Energy is constantly lost in transmission grids due to electric resistance, whereas it is completely conserved in space. Using SPS' is not directly harmful to the environment, given that there are no carbon dioxide emissions produced, so it is a clean and safe energy source [4]. SPS could be potentially better than ground-based photovoltaic (PV) solar power because of the space's virtually unlimited power availability and lower transmission losses [5]. Solar radiation can be more easily accumulated in space than on earth, and it is constantly available [6]. The Japan Aerospace Exploration Agency (JAXA) has made recent progress toward the solar space station, which developed a technological map that shows a 1 GW commercial system by 2030 [5]. Other efforts are located in the ongoing conferences about SPS and wireless power transmission (WPT) and an evaluation by the International Academy of Astronautics (IAA) [7]. If accidents happened in space, they would not be as harmful on earth. It must be noted that the cost of this type of power generation is high, and there is a concern about environmental issues as they relate to the power transmission and launch emissions. The benefits of SPS are a 6-fold increase in available power, longer useful life compared to terrestrial PV systems, and no necessity for energy storage which in conventional systems causes losses up to 40% [8–10]. Space-based solar power consists of two types of technologies: how beams are transmitted to earth and the design of the satellite and receiver module [11]. The first technology is further divided into three categories: the method of collecting solar power in space, transmitting the power to earth, and receiving the power on earth.

On the other hand, concerns about SPS are regulations, adverse health effects, terrorism, and profit. The fear of terrorism is a problem because of the high-power microwave source and the high gain antenna, which produces an extreme surge of energy that could be used as a weapon. The main worry about the SPS is that of profit since they can cost as much as hundreds of millions of dollars over time [5]. This, however, could be understood for a future of clean energy in an economy of growing demand. Regarding the future of the technology, over time more deliveries of the crew, fuel, and other cargo will be needed for the International Space Station (ISS). This information proves that there is a need for the development of more efficient launch technologies. By considering all these factors, the objective of this study is to determine the present possibility and future use of SPS systems.

2. Solar Power Collection

There are various proposed ideas for collecting solar power. Photovoltaic cells that exchange the solar energy for direct current (DC) electricity can be used. Even though this idea seems a desirable choice, silicon cells are susceptible to radiation. This indicates that the accumulator would have to be made of gallium-arsenide (GaAs) cells, which have an increased resistance to radiation. Although these cells are radiation resistant and have efficiencies over 30%, their costs are two orders of magnitude higher than regular silicon solar cells [12]. Another option within photovoltaic systems is thin-film cells. These thin-film cells help to keep costs down, being that they are the cheapest type of PV cells. This arrangement of a system can output efficiency of 6% to 25% that produces an overall electric power flux production of 150 W/m^2. One of the other concepts observed is the space electric power production approach of solar dynamic systems that use heat to run a thermal cycle connected to a generator. This method has a higher efficiency than the PV array/battery systems reaching 20-30% and can distribute continuous power in LEO without batteries [13]. The last possible method for solar collection is to use space solar energy by orbital mirrors of ample size, made of reflective thin film plastics, to converge and provide energy. Additionally, power storage may be required to keep a constant supply of power in the SPS. Smaller satellite systems use on-board storage devices such as lithium polymer or lithium-ion batteries with specific energies between 150-250 Wh/kg [14]. For the SPS case, the PV GaAs solar cell choice can be employed due to its reliability and wide literature available. Likewise, a group of Li-ion batteries can be used to provide the SPS with additional power as a redundant measure to ensure its systems are online at any given time.

3. Microwave Transmission

Since the wired transmission is extremely unfeasible due to the long distances, a low radio frequency in the microwave spectrum (2.4 GHz) or higher within the infrared range is needed. The most popular models for SPS rely on microwave transmission systems to convey the power they collect to earth [15–17]. Microwaves are a form of low-energy electromagnetic radiation that exhibit wavelengths of 1 mm to 30 cm and are well suited for carrying energy through space [15]. These systems convert DC electrical power into radiofrequency (RF) power, which is transmitted through free space and eventually converted from RF power back to DC electrical power [16,18]. For its implementation on SPS, frequencies of 2.4 GHz to 3.3 GHz (13 cm~10 cm) are generally selected because these wavelengths provide for maximum efficiencies over long distances when attenuation over time and losses due to atmospheric effects are considered [15–18]. For a plant of 5 GW total power transmission, the transmitting antenna would need to be on the scale of 1 km in diameter and the rectenna on the scale of 7 km in diameter. These dramatic antenna sizes are needed to create an energy distribution at the rectenna that is non-destructive to the environment, safe for people, and thermally manageable [15,16]. The connection and concentrated delivery of microwaves from the transmitting antenna to the rectenna would be coordinated and maintained via a guiding laser. The uplink between the satellite and the rectenna located on the surface of the earth could be online over 99% of the year due to the geometries of its orbit [15,18]. This entails nearly 24 hours of solar power generation. This technology is desirable because it offers relatively high-efficiency conversion and energy delivery in the range of 50%-75% DC to DC efficiency [19]. In addition to the more extended collection periods and efficient power delivery allowed by microwave transmission, the photovoltaic cells could maintain an ideal relationship with the position of the sun, further maximizing their efficiency. In terms of possible challenges, the likelihood of a malfunction occurring in the systems controlling the uplink between the antenna and rectenna poses a potential hazard in the form of a straying microwave beam. If power concentrations are above allowable levels, this potential malfunction could pose a threat to the health of humans and other organisms. For this and for legal reasons, power concentrations reaching the ground would need to be ensured below allowable levels as regulated by the Environmental Protection Agency (EPA) in the United States or the equivalent regulating body in each given country utilizing this technology. This raises another issue: the lack of international precedence for such a utility. An SPS system utilizing microwave power transmission in the gigawatt range would involve every political territory surrounding the equator that it passes over, necessitating new international guidelines and agreements to regulate and allow for such systems. For obvious reasons, this could prove to be a particularly reluctant concern. Furthermore, due to the power intensity of such a signal, fears about this technology being weaponized may arise. Transmitting a microwave beam in the gigawatt range of power through the air will completely erase any wireless communications attempting to cross its path and heavily distort communications even at considerable distances from the rectenna. This impasse is the primary issue limiting the broader usage and development of wireless power transmission historically [16].

Land usage and availability remain a problem regarding the microwave power transmission, as they have for other conventional energy production methods, due to the dramatic scale the rectifying antenna requires [15]. This necessity highlights land as the primary limiting factor involved in the implementation of a viable SPS utilizing microwave power transmission and diminishes the perceived potential for the scalability of such systems. Although low energy microwaves on a scale of up to a few millimeters are generally believed to not affect humans or animals, there exist no definitive studies which demonstrate the impact or lack thereof of prolonged human exposure to moderate concentrations of waves in the infrared spectrum. This system's unprecedented and dramatic nature may produce unforeseen ecological and human risks.

4. Effects of radiation on solar cells and electrical components

Radiation is a significant factor in orbit. To account for this, both spacecraft and equipment require extensive shielding against it, thus making them heavier, which is not optimal for space missions [20]. Satellite semiconductor materials are especially susceptible to collected radiation doses. In harsh space conditions, highly charged particles and electromagnetic rays constantly bombard electrical components and solar cells, causing continuous performance degradation. Charged particles consist of electrons with energies of up to 10 MeV and protons that can carry hundreds of megaelectron volts of energy. Cosmic rays also constitute a problem due to their high ionization capabilities, ability to carry gigaelectron volts of energy [21]. When these particles impact the semiconductor material, the energy carried by the particle is transferred to the atoms, displacing them from their initial positions. The shifted atoms will be incapable of efficiently conducting current in the electric components, reducing the materials' conductivity. In the case of solar cells, the displacement damages caused by the shifted atoms will decrease the carrier's diffusion length, subsequently producing diminished performance [22,23]. To efficiently shield electronic devices and solar units in the SPS from radiation, it is necessary to know how vulnerable these elements are, the yearly dose presented at geostationary orbit (GEO), and the lightest materials that will provide the maximum shielding. Bhat et al. [24] determined the yearly radiation dose at GEO using radiation-sensitive field-effect transistors (RADFETs). Different aluminum spherical covers with variable thickness were used to shield the system components. The results showed that for an aluminum shield thickness of 11 mm the yearly radiation amount was four orders of magnitude lower than those elements that did not present protection. From Figure 1, it is possible to observe that the optimal aluminum thickness for electric component shielding is located between 7 mm and 11 mm, since thinner walls would dramatically increase the radiation impact, and thicker walls would only be able to produce marginal decreases in the radiation effects [24]. Although it is essential to keep in mind that the added weight caused by the implementation of shielding would increase launching costs, therefore, thinner walls (< 7 mm) for system protection would be preferable. Even if a wall thickness of 11 mm is chosen, the amount of radiation the electric systems are bombarded with is still 700 times higher than on earth. Therefore, lighter materials that can be more effective against radiation are needed, such as bismuth oxide doped glasses [25]. Moreover, solar cells in the SPS would also be drastically affected by ionizing radiation, therefore, it is essential to understand the failure mechanisms presented in them. Irradiation environments cause ionization and shift damage (non-ionizing) failure processes in solar cell units [26]. The latter is the leading cause of degradation in extraterrestrial solar panels. Figure 2 and Figure 3 show the relative damage coefficient for dual GaAs/Ge junction solar cells as functions of proton and electron energy, respectively.

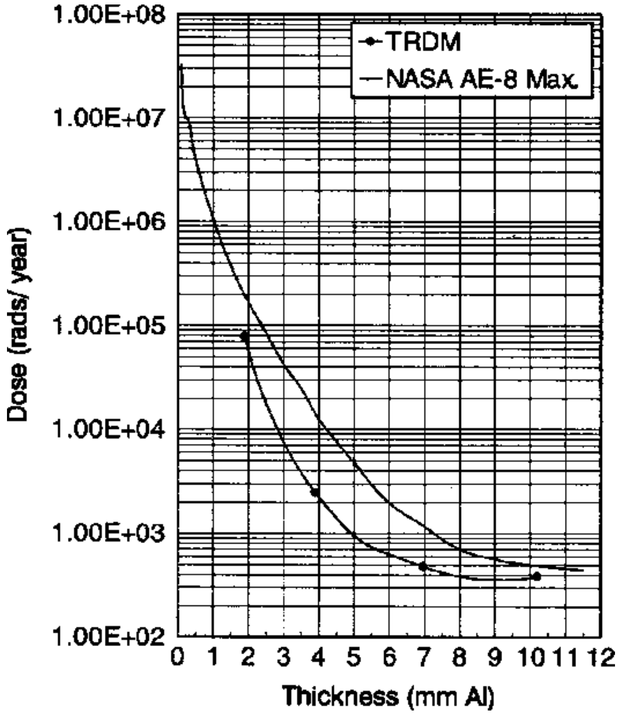

Figure 1. Ionizing radiation dose as a function of aluminum dome thickness [24]

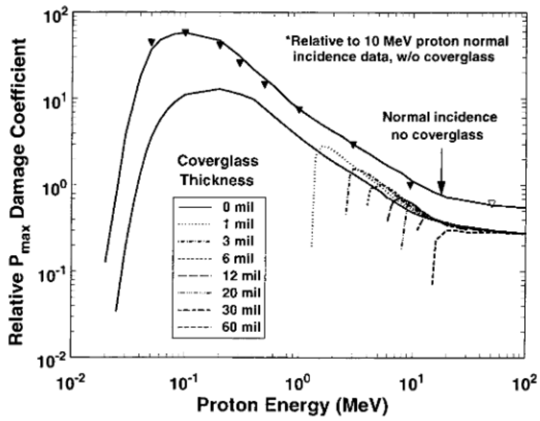

Figure 2. GaAs/Ge Solar cell relative damage as a function of proton energy for different cover glass thickness [27]

It is possible to observe that to maximize useful solar cell life, it is necessary to have at least a 6 cm cover glass plate on the panels. The employment of such a plate would keep proton damage at a minimum, but it would not be effective against high-energy electron impacts (over 10 MeV). Contrarily, these high-energy particles are comparatively uncommon (below 1% of all given protons and electron impacts have energy over 300 keV, see Figure 4) thus, the employment of a 3 cm thick cover glass or thinner is also viable to eliminate damaging radiation [28]. Another option is the implementation of nanowire array solar cells that may reduce the need for shielding, particularly protons with energies between 100-350 keV and 1 MeV electron [20].

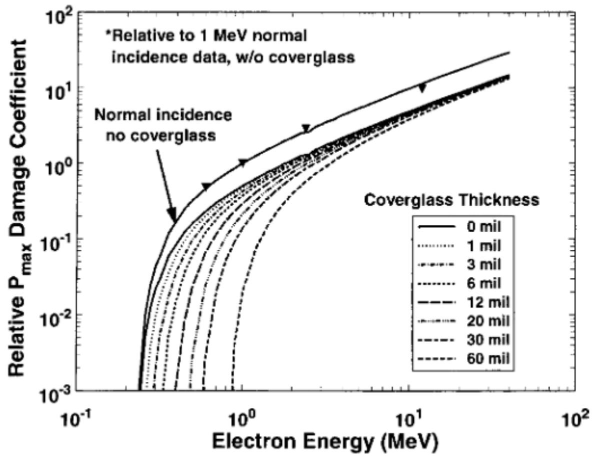

Figure 3. GaAs/Ge Solar cell relative damage as a function of electron energy for different cover glass thickness [27]

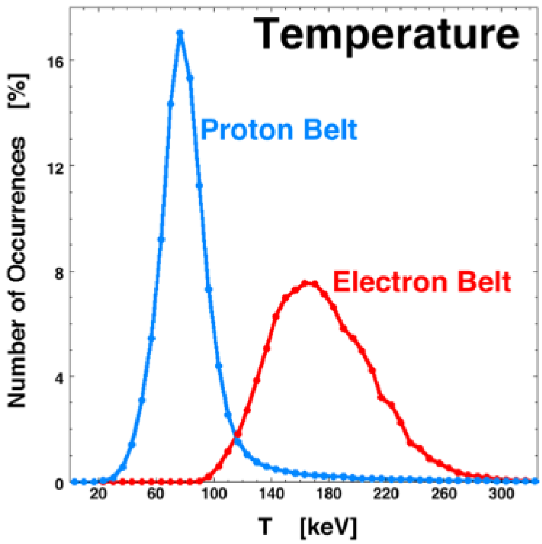

Figure 4. Probability distribution of particle occurrence in geosynchronous orbit as a function of their temperature (energy) [28]

Since weight is such a critical factor for the SPS design, it is necessary to determine the estimated mass addition for a 5 GW SPS with a solar panel surface area of 14 km² at 368.82 W/m². The borosilicate type CMG cover glass is a typical material used to cover GaAs solar cells due to its superior optical, radiation, solar absorbance, and emissivity properties [29,30]. At a density of 2554 kg/m³, if 1 cm CMG cover glass thick is chosen the total shielding mass would be 3.5756 $*10^8$ kg making the project infeasible. Therefore, the protective thickness must be reduced at the expense of radiation protection. If 100 microns of CMG shields are used, the total mass is significantly decreased to 3.5756 $*10^6$ kg. Figure 5 shows the total SPS mass for different shielding thicknesses. This is still incredibly heavy, but it would make the SPS possible while simultaneously obtaining radiation protection. In conclusion, radiation shielding can be achieved with a thickness of 100 microns of CMG cover glass at the expense of extra cost and weight.

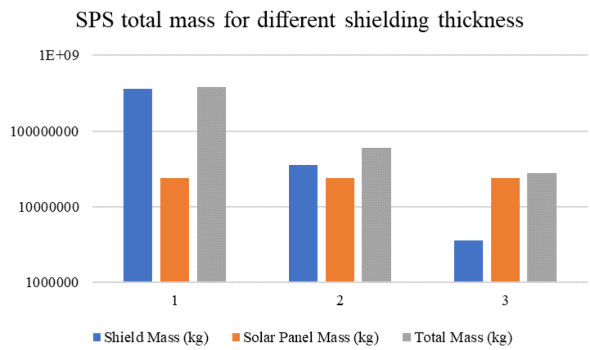

Figure 5. SPS total mass for CMG cover glass thickness of 0.01, 0.001, and 0.0001 m

5. Propulsion system

In terms of the desired orbit, NASA stated that the best place for a solar space station is in GEO. By placing the system in GEO, it would be possible to maintain a fixed connection between the transmitting and receiving antenna by keeping the SPS fixed relative to the surface of the earth. This would enable the energy supply to large population zones around the planet [31]. For the SPS to stay in orbit, avoid collisions, and adjust the effects of solar pressure (which is going to produce substantial deviations due to the SPS's ~14 km² surface area) it will need a propulsion system capable of quickly changing its trajectory. The fuel mass must be kept to a minimum to prevent increases in launch cost while simultaneously having enough to complete the spacecraft mission time. To accomplish this objective, the thrusters must be as efficient as possible (high specific impulse) while at the same time being able to provide enough thrust for quick reaction maneuvers. Electric thrusters are a promising option due to their increased efficiencies, although most are incapable of producing enough thrust. Even though the thrust produced by electrostatic acceleration systems is around two orders of magnitude lower than their chemical counterparts, they can achieve higher specific impulses. A desirable propulsion system for the SPS could be that of the Hall thruster. They can achieve specific impulse values of ~1500 seconds, which is almost ten times higher than those from chemical combustion engines. It is also worth mentioning that Hall propulsor efficiency increases as the power supplied rises. Hall engines work by creating a radial magnetic field in their circular ionization chamber capable of accelerating electrons. Then a neutral gas, generally xenon, is released into the chamber to be ionized; this ionized gas is later expelled from the chamber at elevated velocities along with a stream of electrons to maintain the spacecraft's electrical neutrality [32]. The SPS can employ Hall engines because they can provide enough thrust (0.01 N-0.25 N) to perform fast changes in the trajectory; they also have the capability of increasing their produced thrust from their known limits since no technical limitations have been found when supplying more than 100 kW of power [33,34].

6. Comparison With Terrestrial Solar Power Generation (TSPS)

It is crucial to evaluate the efficiency of space solar stations to conventional solar power plants. The average solar power per unit area on the surface of the earth is 250 W/m² compared to ~1360 W/m² in space near earth [35]. The maximum efficiency of conventional photovoltaic cells is around 20%, while multi-junction photovoltaic cells designed for satellites can maintain efficiencies of around 30% and 35% [22,36]. This results in an overall power production of 50 W/m² on earth and 409.8 W/m² on the SPS system. When considering the efficiency of microwave power transmission of 90% the power delivered to earth by the SPS will be 368.82 W/m² of PV surface [15]. However, over the course of a day, this loss is compensated for by the fact that solar exposure is continuous in the SPS, meaning that the average power production will be maintained at 368.82 W/m² compared to the terrestrial panel, which will average only 14.6 W/m² over the course of the day. This means that in terms of actual power generation, conversion and transmission of solar power is over twenty-five times as efficient on SPS systems when compared to terrestrial ones, with a percent difference of 184.8%. However, this efficiency neglects one critical factor, which is the land area required for the rectenna. Therefore, the true power generated in terms of power flux (W/m²) from SPS systems will be limited by the power flux density allowable, which is generally dictated by safety guidelines established by government organizations. As this is the case, the true efficiency in W/m² of power generation using a SPS transmitting 5 GW at 3.3 GHz at 90% efficiency, in terms of land area needed on earth, is 100 W/m² [15]. Even though this is a critical issue, the SPS is still over six times more efficient (in terms of surface coverage) than conventional PV systems.

7. Cost analysis: current and predicted budget

The main problem with the current SPS stance is its immense size: a 1 km transmitting antenna, 7 km receiving antenna, and ~14 km² of solar panels are needed to produce the desired 5 GW of power at the power density of 368.82 W/m². Therefore, the SPS will be extremely heavy which causes a dramatic increment in the station's initial price due to expensive launch costs to GEO. If an area density of 1.76 kg/m² (3 mm thick) for solar panels is considered, the solar panels would weigh an estimated 23859 metric tons. To put this size into perspective, the SPS panels without the transmitting antenna would be around 47 times heavier than the International Space Station (ISS). Although launch costs to Low Earth Orbit (LEO) have been reduced by a factor of 20 over the past two decades, the current cheapest cost per kilogram to LEO has been achieved by SpaceX's Falcon Heavy with a value of 1400 $/kg [37]. The cost to take a kilogram of payload to GEO orbit is generally six times greater than that of LEO. These factors result in an expense of around $200 billion just for the launching phase of the station panels. If the shielding weight is factored in, that would be an additional $30 billion in launching costs. The manufacturing costs of silicon solar cells would also have to be included; considering a solar panel price of 100 $/m² the total expenditure would amount to $5 billion. It is necessary to consider that the actual solar cells needed are made of Gallium-Arsenide, which is significantly more expensive when compared to silicon cells which would further drive costs up. Additionally, the development of both transmitting and receiving antenna would also have to be considered, the former further increasing launch costs since it is going to be located alongside the solar units in space. An estimate for the development and manufacture of both receiving and transmitting antennas would be around $20 billion. This estimation was performed by comparing the total surface area of both transmitting and receiving antenna with the FAST telescope area, then that ratio was multiplied by the FAST construction cost of $100 million [38]. These considerations would make the initial project cost $255 billion, rendering the project presently impractical. From Figure 6 it is possible to observe the cost distribution for the SPS at the current 2022 US dollars (USD).

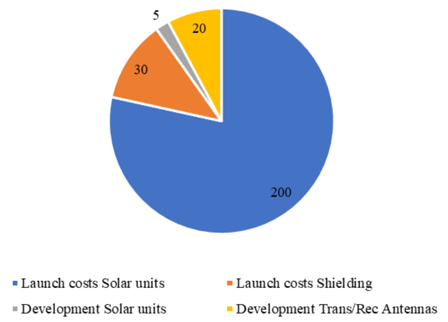

Figure 6. Current SPS total cost distribution in 2022 billion USD

Therefore, to make the project economically viable, launch costs to GEO must be decreased by a factor of 10 when compared to the current prices to LEO performed by the Falcon Heavy rocket (~140 $/kg), solar cell efficiency must be increased to 40%, and solar cell density should be reduced from 1.76 kg/m² to 1 kg/m² on 3 mm thick units while improving their radiation resistance. Making an estimation by including the different assumptions stated above, a cost of $48 billion can be obtained. Figure 7 shows the cost distribution after these predictions in 2022 USD. Although the new costs for the solar power station could be dramatically reduced, this final overall price is still incredibly expensive for just one private company to assume; therefore, international support and private consortiums are essential to improve the feasibility of the task.

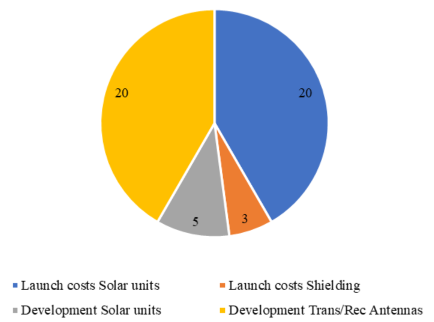

Figure 7. Predicted SPS total cost distribution in 2022 billion USD

8. International competition and recent progress

As previously mentioned, launch costs to LEO have been reduced by a factor of 20 over the past two decades, which has enabled space accessibility for a broader range of organizations. These extraordinary launch cost reductions along with continuous breakthroughs in Photovoltaic technology, WPT, and radiation shielding methods, have reignited the interest of international organizations, private companies, and governments in space solar energy [39]. In the US, through sponsored research by Northrop Grumman, a group of scientists at the California Institute of Technology asserts to have developed an SPS model capable of emitting solar energy from space [40]. The US government has also shown some interest in the idea over the years; in 2007 the National Security Space Office (NSSO), through its report "Space-Based Solar Power as an Opportunity for Strategic

Security" concluded that this technology could advance the United States' geopolitical stance in the contemporary space race [41]. In this regard, the US military leads the most important effort in the country by allocating $178 million towards solar space power research and development [40]. In this new space race, private companies are now capable of contributing towards space solar technology. Firms such as Solaren, PowerSat Corporation, and Space Energy are tackling different challenges under this project. Companies are unifying efforts to achieve this, as it is the case with Solaren who partnered with Pacific Gas & Electric to deliver power from space. On the other hand, PowerSat Corporation has focused on the technological challenges of the project. This eager participation from the private sector shows how this technology has a promising future in relation to humanity's net-zero emissions goal [41]. The European Space Agency (ESA) is also interested in this technology. The agency has started an initiative to demonstrate the SPS potential for providing energy by selecting 13 ideas for funding. Since solar power from space is an interdisciplinary problem, these research topics deal with distinct challenges such as sunlight collection or wireless transmission safety [42]. In 2021, the ESA hosted a workshop about solar power satellites with the goal of investigating the SPS impact on fighting climate change. In addition, the space agency also performed a cost analysis to determine the feasibility of the SPS business as a source of clean energy [42]. China is also trying to obtain an advantage in this possible new market. The country is preparing to launch a demonstrative SPS around the 2030 and a commercial station by 2050 [39]. To achieve this deadline, the Chinese state has funded the Bishan project, which is focused on creating a floating platform that will rise 300 meters above the ground and attempt to transfer the solar energy captured to the surface. If successful it will be relocated at 22 km above earth surface to continue testing [43]. They also expect to complete their high voltage transmission line and wireless energy transfer tests by the end of the decade, which will allow the rapid scaling of WPT technology for the SPS [40]. Another country that has also started to commercialize solar space technology by 2050 is Japan. In 2017, the Japan Aerospace Exploration Agency (JAXA) announced that it would have an SPS online by the first half of this century. The Japanese agency has partnered with Mitsubishi to develop a demonstration system capable of supplying megawatts of energy and has redirected many of its resources into WPT and robotic assembly technology research [44,45]. Considering these aspects, SPS technology has the potential to change the world. In 2021, the energy consumed in the US was about 4 trillion kilowatt-hours [46]. If only one 5-GW solar power station is considered, it would be able to provide 1% of all the energy US citizens consume in a year, assuming it would be online on a daily basis. It is also important to note that this power would not be constrained by weather patterns, as it is the case for solar and wind, and price fluctuations due to geopolitical conflicts, unlike oil and natural gas. However, and most importantly, this technology gives humanity the chance to achieve a future with zero net emissions. Therefore, it is possible to conclude that more international cooperation is needed to accomplish this goal.

9. Conclusion

The feasibility of solar satellite space stations was explored through the lenses of current technology. Present innovations were proposed for the development of the system while simultaneously discussing the challenges it would face. It was determined that the most beneficial orbit to locate the system was at GEO because it would allow the station to be on a fixed-point relative to earth. Gallium-Arsenide PV cells can be a viable option for power collection due to their high efficiencies and radiation resistance properties. Regarding the power transmission from the station to the receiving antenna, the desired frequencies are from 2.4 GHz to 6 GHz, being these the magnitudes that present the least atmospheric attenuation and thus being the most efficient to transmit power. Using these frequencies, a total of 5 GW of power can be achieved at 90% efficiency. When it comes to ionizing radiation, a CMG cover of 100 microns can be used to reduce solar cell damage. Moreover, it was determined that Hall thrusters would be the optimal propulsion system for the station since they can provide the most advantageous combination between fuel efficiency and thrust. In terms of present viability, it was determined that the SPS is not economically possible mainly because of launch mission costs to GEO. Technical challenges such as reduction of solar unit density, increase in cell efficiency, and radiation shielding are some of the most important factors to make the SPS a viable option. In addition, a project of this magnitude would require the cooperation of several entities to make it a reality requiring international and private support. In conclusion, more research must be done regarding the reduction of payload costs to LEO and the development of radiation-resistant and efficient solar units to provide a future where satellite power energy is possible.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The author adheres to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Conflict of interest

The authors declare no potential conflict of interest.

References

[1] J.C. Mankins, N. Kaya, M. Vasile, SPS-ALPHA: The first practical solar power satellite via arbitrarily large phased array (A 2011-2012 NASA N1AC project), in: Proceedings of the International Astronautical Congress, IAC, 2012. https://doi.org/10.2514/6.2012-3978.

[2] S. Weitemeyer, D. Kleinhans, T. Vogt, C. Agert, Integration of Renewable Energy Sources in future power systems: The role of storage, Renewable Energy. 75 (2015). https://doi.org/10.1016/j.renene.2014.09.028.

[3] ROUGE JD, A.F. Study, Space-Based Solar Power As an Opportunity for Strategic Security Report to the Director , National Security Space Office, 2007.

[4] A. Smith, T.B. Johansson, R.T. Watson, M.C. Zinyowera, R.H. Moss, Space Solar Power: An Idea Whose Time Will Never Come?, Renewable Energy. (2003).

[5] B.S. Sasaki, How Japan Plans to Build an Orbital Solar Farm, IEEE Spectrum. (2014).

[6] J.C. Mankins, A fresh look at space solar power: New architectures, concepts and technologies, Acta

Astronautica. 41 (1997). https://doi.org/10.1016/S0094-5765(98)00075-7.

[7] J.C. Mankins, N. Kaya, Solar energy from space: An international assessment of opportunities, issues and potential pathways forward abstract, in: International Astronautical Federation - 59th International Astronautical Congress 2008, IAC 2008, 2008.

[8] D.R. Criswell, R.G. Thompson, Data envelopment analysis of space and terrestrially-based large scale commercial power systems for earth: A prototype analysis of their relative economic advantages, Solar Energy. 56 (1996). https://doi.org/10.1016/0038-092X(95)00113-6.

[9] P.R. Harris, Solar power satellites - The emerging energy option, Space Policy. 10 (1994). https://doi.org/10.1016/0265-9646(94)90045-0.

[10] J.K. Strickland, Advantages of solar power satellites for base load electrical supply compared to ground solar power, Solar Energy. 56 (1996). https://doi.org/10.1016/0038-092X(95)00087-8.

[11] R.H. Nansen, Wireless power transmission: the key to solar power satellites, IEEE Aerospace and Electronic Systems Magazine. 11 (1996). https://doi.org/10.1109/62.484148.

[12] M. Williams, Stanford breakthrough could make better chips cheaper, Https://Www.Computerworld.Com/Article/2901383/Stanford-Breakthrough-Could-Make-Better-Chips-Cheaper.Html . (2015).

[13] N. Lior, Power from space, Energy Conversion and Management. 42 (2001). https://doi.org/10.1016/S0196-8904(01)00040-1.

[14] F. Leverone, M. Pini, A. Cervone, E. Gill, Solar energy harvesting on-board small satellites, Renewable Energy. 159 (2020). https://doi.org/10.1016/j.renene.2020.05.176.

[15] P.E. Glaser, O.E. Maynard, J. Mackovciak, E.L. Ralph, FEASIBILITY STUDY OF A SATELLITE SOLAR POWER STATION., NASA Contractor Reports. (1974).

[16] W.C. Brown, The History of Power Transmission by Radio Waves, IEEE Transactions on Microwave Theory and Techniques. 32 (1984). https://doi.org/10.1109/TMTT.1984.1132833.

[17] R.M. Dickinson, Power in the sky: Requirements for microwave wireless power beamers for powering high-altitude platforms, IEEE Microwave Magazine. 14 (2013). https://doi.org/10.1109/MMM.2012.2234632.

[18] E.E. Eves, Beamed Microwave Power Transmission and its Application to Space, IEEE Transactions on Microwave Theory and Techniques. 40 (1992). https://doi.org/10.1109/22.141357.

[19] R.M. Dickinson, W.C. Brown, Radiated microwave power transmission system efficiency measurements, NASA STI/Recon Technical Report N. 75 (1975).

[20] P. Espinet-Gonzalez, E. Barrigón, G. Otnes, G. Vescovi, C. Mann, R.M. France, A.J. Welch, M.S. Hunt, D. Walker, M.D. Kelzenberg, I. Åberg, M.T. Borgström, L. Samuelson, H.A. Atwater, Radiation Tolerant Nanowire Array Solar Cells, ACS Nano. 13 (2019). https://doi.org/10.1021/acsnano.9b05213.

[21] A. Hamache, N. Sengouga, A. Meftah, M. Henini, Modeling the effect of 1 MeV electron irradiation on the performance of n+-p-p+ silicon space solar cells, Radiation Physics and Chemistry. 123 (2016). https://doi.org/10.1016/j.radphyschem.2016.02.025.

[22] J. Li, A. Aierken, Y. Liu, Y. Zhuang, X. Yang, J.H. Mo, R.K. Fan, Q.Y. Chen, S.Y. Zhang, Y.M. Huang, Q. Zhang, A Brief Review of High Efficiency III-V Solar Cells for Space Application, Frontiers in Physics. 8 (2021). https://doi.org/10.3389/fphy.2020.631925.

[23] A. ur Rehman, S.H. Lee, S.H. Lee, Silicon space solar cells: progression and radiation-resistance analysis, Journal of the Korean Physical Society. 68 (2016). https://doi.org/10.3938/jkps.68.593.

[24] B.R. Bhat, N. Upadhyaya, R. Kulkarni, Total radiation dose at geostationary orbit, IEEE Transactions on Nuclear Science. 52 (2005). https://doi.org/10.1109/TNS.2005.846881.

[25] S.P. Singh, B. Karmakar, Bismuth oxide and bismuth oxide doped glasses for optical and photonic applications, in: Bismuth: Characteristics, Production and Applications, 2012.

[26] E. el Allam, C. Inguimbert, S. Addarkaoui, A. Meulenberg, A. Jorio, I. Zorkani, NIEL calculations for estimating the displacement damage introduced in GaAs irradiated with charged particles, in: IOP Conference Series: Materials Science and Engineering, 2017. https://doi.org/10.1088/1757-899X/186/1/012005.

[27] J.M. Hu, Y.Y. Wu, Z. Zhang, D.Z. Yang, S.Y. He, A study on the degradation of GaAs/Ge solar cells irradiated by <200 keV protons, Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms. 266 (2008). https://doi.org/10.1016/j.nimb.2007.11.010.

[28] J.E. Borovsky, T.E. Cayton, M.H. Denton, R.D. Belian, R.A. Christensen, J.C. Ingraham, The proton and electron radiation belts at geosynchronous orbit: Statistics and behavior during high-speed stream-driven storms, Journal of Geophysical Research: Space Physics. 121 (2016). https://doi.org/10.1002/2016JA022520.

[29] P.A.White, A COVERGLASS FOR GaAs SOLAR CELLS , IEEE Conference on Photovoltaic Specialists. (1990).

[30] E. Plis, V.J. Murray, D.P. Engelhart, K.W. Fulford, A. Sokolovskiy, D.C. Ferguson, R.C. Hoffman, Solar panel coverglass degradation due to the simulated GEO environment exposure, in: 2021. https://doi.org/10.1117/12.2588655.

[31] Claybaugh W, Redmond C, Commercial space transportation study, (1997). http://stp.msfc.nasa.gov/stpweb/Co (accessed April 15, 2022).

[32] D. Krejci, P. Lozano, Space Propulsion Technology for Small Spacecraft, Proceedings of the IEEE. 106 (2018). https://doi.org/10.1109/JPROC.2017.2778747.

[33] I. Levchenko, S. Xu, G. Teel, D. Mariotti, M.L.R. Walker, M. Keidar, Recent progress and perspectives of space electric propulsion systems based on smart nanomaterials, Nature Communications. 9 (2018). https://doi.org/10.1038/s41467-017-02269-7.

[34] S.J. Hall, S.E. Cusson, A.D. Gallimore, 30-kW Performance of a 100-kW Class Nested-channel, 34th International Electric Propulsion Conference. (2015).
[35] MUNCHO J. MBUNWE, UDOCHUKWU B. AKURU, HILARY U. EZEA, OGBONNAYA I., Some Aspects of Future Energy Generation in Using of Solar Power Satellites, International Journal of Analysis and Applications. (2020). https://doi.org/10.28924/2291-8639-18-2020-117.
[36] B.B. GARDAS, M.V. TENDOLKAR, DESIGN OF COOLING SYSTEM FOR PHOTOVOLTAIC PANEL FOR INCREASING ITS ELECTRICAL EFFICIENCY, International Journal of Mechanical and Industrial Engineering. (2013). https://doi.org/10.47893/ijmie.2013.1129.
[37] H.W. Jones, The Recent Large Reduction in Space Launch Cost, 48th International Conference on Environmental Systems. (2018).
[38] D. Li, Z. Pan, The Five-hundred-meter Aperture Spherical Radio Telescope project, Radio Science. 51 (2016). https://doi.org/10.1002/2015RS005877.
[39] The Emerging Competition for Space Solar Power | Global Policy Journal, (n.d.). https://www.globalpolicyjournal.com/blog/21/10/2019/emerging-competition-space-solar-power (accessed April 23, 2022).
[40] China plans a solar power play in space that NASA abandoned long ago, (n.d.). https://www.cnbc.com/2019/03/15/china-plans-a-solar-power-play-in-space-that-nasa-abandoned-long-ago.html (accessed April 24, 2022).
[41] L.W. Wood, Projecting power: The security implications of space-based solar power, Bulletin of the Atomic Scientists. 68 (2012). https://doi.org/10.1177/0096340211433005.
[42] ESA - ESA reignites space-based solar power research, (n.d.). https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/ESA_reignites_space-based_solar_power_research (accessed April 23, 2022).
[43] ETERNAL ENERGY | NewsChina Magazine, (n.d.). http://www.newschinamag.com/newschina/articleDetail.do?article_id=6846&section_id=17&magazine_id=71 (accessed April 24, 2022).
[44] D. Cyranoski, Japan sets sights on solar power from space, Nature. 462 (2009). https://doi.org/10.1038/462398b.
[45] Research on the Space Solar Power Systems (SSPS) | JAXA | Research and Development Directorate, (n.d.). https://www.kenkai.jaxa.jp/eng/research/ssps/ssps-index.html (accessed April 25, 2022).
[46] Use of electricity - U.S. Energy Information Administration (EIA), (n.d.). https://www.eia.gov/energyexplained/electricity/use-of-electricity.php (accessed April 25, 2022).