AMERICAN FOREIGN POLICY COUNCIL
Space Policy Initiative

Space Policy Review

The Promise of Space-Based Solar Power

By: Cody Retherford

The Big Picture

- Space-based solar power (SSP) satellites will beam energy through the Earth's atmosphere to rectifying antennas, which will convert the electromagnetic energy to electricity.
- SSP satellites have the potential to provide gigawatt levels of renewable electricity 24 hours a day anywhere in the world.
- China has an SSP program that supports its strategy to become a global space power by 2045 and a global power by 2049, and to become carbon neutral by 2060.
- Commercial-level SSP will reduce dependence on fossil fuels, dramatically shift global energy markets, build economic and geopolitical influence, and accelerate military and space power projection.
- SSP will increase commercial and residential energy, boost industrial manufacturing and mining, support advanced transportation services, and strengthen military operations.
- The U.S. government needs to prioritize research and funding for SSP and develop an implementation plan with concrete milestones.

Energy drives policy. Markets are dictated by energy flows, and nations with excess energy capacity have an economic advantage. As evidenced recently in Russia's war in Ukraine, nations' responses can be dictated by their energy dependence on Russia. Unfortunately, carbon-based energy sources are finite, and the impact of excess atmospheric carbon on the climate has necessitated a reduction in fossil fuel use. The solution to global demand for energy may be found in the form of solar power, not in the traditional terrestrial sense but, instead, through energy collection in space.

Space-based solar power (SSP) satellites have the potential to change human life dramatically, in the same manner as previous satellite technologies such as satellite communications and global navigation satellite systems. The United States must execute a series of legislative and policy actions to support the U.S. space community's efforts to compete with China over this key technology.

SSP satellites are a combination of proven photovoltaic solar energy collection, solar energy conversion to microwaves or lasers, and wireless power beaming technologies. SSP satellites will beam energy through the Earth's atmosphere to rectifying antennas that will convert the electromagnetic energy to electricity. SSP satellites have the potential to provide gigawatt levels of renewable electricity 24 hours a day anywhere in the world. Several recent studies, sponsored by the U.K. Department for Business, Energy & Industrial Strategy,[1] the U.S. Department of Defense,[2] the European Space Agency (ESA),[3] RAND

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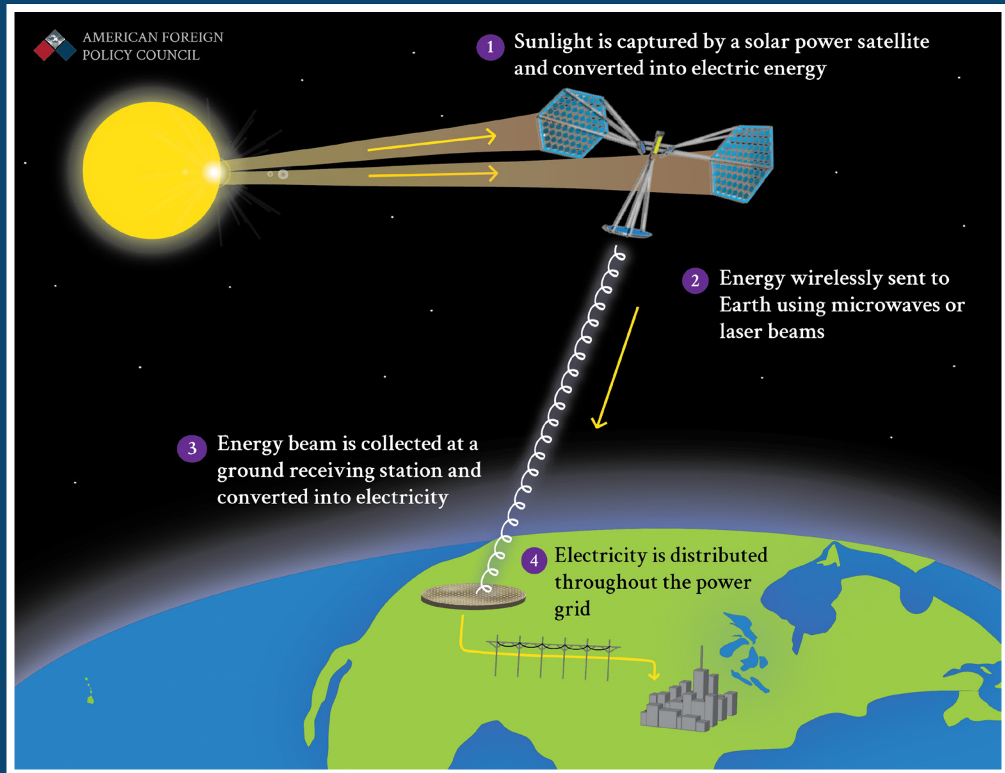
Corporation,[4] the Aerospace Corporation,[5] the Progressive Policy Institute,[6] and CitiGroup[7] all suggest that SSP will become critical in the coming decades as energy insecurity and climate change drive decision making by states in several areas including to meet international emissions goals, to compete in global energy markets, to power sustainable manufacturing, agricultural, transportation, and shipping industries, and to advance military and space capabilities. SSP has the potential to provide massive advantages to states capable of developing the technology. These include innovations across the energy sector, in space access mobility and logistics (SAML) and, in particular, in-space servicing, assembly, and manufacturing (ISAM).[8]

Figure 1. Space-based Solar Power Overview



Source: American Foreign Policy Council and U.S. Department of Energy

Placing solar energy collection in space provides solutions to several problems with current terrestrial solar power collection systems. Approximately 47 percent of solar energy reaches the Earth's surface, which limits terrestrial solar panel collection.[9] Solar irradiance and weather patterns vary widely across Earth, preventing some countries from collecting solar energy efficiently.[10] SSP satellite arrays in space circumvent atmospheric reflection and limited irradiance of solar energy, allowing collection of 99.9 percent of solar energy directed at a satellite. Microwaves beamed through the atmosphere will retain 99.7 percent of their energy.[11] Lasers will be affected by weather and the atmosphere and are expected to retain lower percentages of energy. Commercial SSP platforms will be microwave based, whereas military and space applications may use both beaming methods.

Although no tests of a complete demonstrator have occurred in orbit, several research efforts are progressing toward that goal. China is executing a long-term SSP program in support of its strategy to become a global space power by 2045 and a global power by 2049,[12] and to be carbon neutral by 2060. The United States, Japan, and the European Union are conducting experiments and studies with short-term goals to demonstrate SSP technologies. Several other states, including Russia, India, Australia, and the United Kingdom, are also exploring potential programs. SSP research and development presents an opportunity for the United States to collaborate with allies and partners and to compete against adversarial states seeking to dominate the technology.

SSP satellites are a critical future technology that have the potential to provide energy security, drive sustainable economic growth, support advanced military and space exploration capabilities, and help fight ongoing climate change. ***The first state to implement commercial-level SSP will reduce its dependence on fossil fuels; dramatically shift global energy markets; build economic and geopolitical influence over neighbors, rivals, and states dependent on energy from the SSP provider; and accelerate military and space power projection.***

Applications

Table 1 summarizes the numerous SSP benefits, including applications for electricity production and the industrial, transportation, and military sectors.

Table 1. Space-based Solar Power Appilcation Benefits

Sector	SSP Application Benefits
Electricity	Potential to provide clean energy for commercial, and residential, and office electricity requirements Offsets the demand for energy increase as efforts to decommission oil, natural gas, coal, and nuclear power plants expand
Industrial	Potentially provides power to a variety of industries, including manufacturing, mining, agriculture, transportation, and shipping Reduces the reliance on fossil fuels, which account for the majority of industrial energy Enables and reduces the cost of energy-intensive water desalination facilities providing more clean water
Transportation	Supports the expanding use of electric personal vehicles, commercial shipping vehicles and vessels, and transportation vehicles including buses, trains, and planes Provides a viable option, particularly to remote areas, supporting shipping trucks, which will likely become primarily autonomous and electric over the next three decades Enables electrified shipping (90 percent of trade moves via shipping vessels)
Military	Revolutionizes logistical support and power delivery for expeditionary military operations Could support future drones as the United States replaces the retiring MQ-9 and RQ-4 with extreme-endurance platforms

ELECTRICITY APPLICATIONS

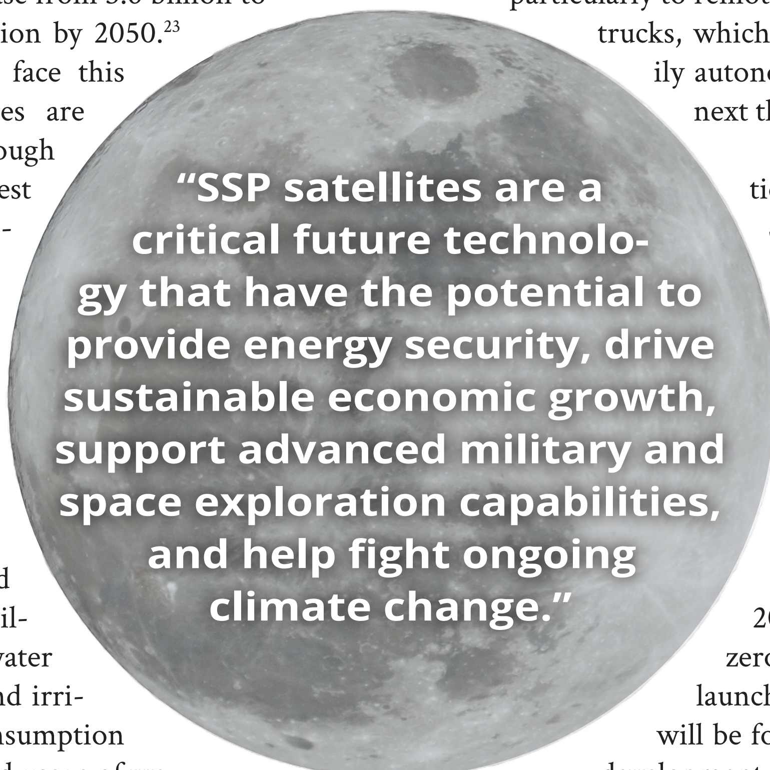
Space-based solar power has the potential to provide clean energy for commercial and residential electricity requirements of an ever-increasing global population. The Population Reference Bureau estimates that the world population will increase to 9.9 billion by 2050.[13] The World Bank provides a similar estimate at 9.7 billion by 2050.[14] The U.S. Census Bureau expects that the United States alone will contribute 56 million additional people to the world's population by 2050.[15] ***This 2 billion person increase in the global population will place extreme strain on energy production and distribution infrastructure, potentially creating widespread energy insecurity.*** The additional population will also place extreme strain on water and food supplies. The United Nations expects a 30 percent increase in demand for water and a 50 percent increase in demand for food by 2050.[16]

The population increase in conjunction with residential, commercial, industrial, and transportation expansion to meet the demands of the population is expected to cause global electricity demand to rise from 25 trillion kilowatt hours in 2020 to 45 trillion kilowatt hours in 2050.[17] Demand for solar power will increase both as demand for energy increases and as efforts to decommission oil, natural gas, coal, and nuclear power plants expand. Solar energy will replace significant portions of that loss while also accounting for new energy demand.[18] SSP can provide solar energy operating at scales possible to cope with future global demand.[19] Studies by the Japanese and American space agencies demonstrate the potential for SSP satellites to provide gigawatt levels of electricity at a levelized cost of electricity well below 10 cents per kilowatt hour.[20] The costs are expected to decline as SSP technology and employment of the technology mature between now and 2050.

INDUSTRIAL APPLICATIONS

Space-based solar power is applicable to a variety of industries, including manufacturing, mining, agriculture, transportation, and shipping operations. U.S. industrial energy use accounted for approximately 36 percent of all U.S. energy production in 2020.[21] Fossil fuels accounted for the majority of industrial energy usage with renewables providing less than 10 percent in 2020.[22] The chemical, petroleum, plastic, metal, and wood industries are extremely energy intensive, contributing significant particulate and greenhouse gases to the environment. Industrial manufacturing will directly benefit from SSP as focus shifts toward renewable energy. Rectifying antennas placed on industrial campuses, former fossil fuel plants, oil rigs, or in remote locations will be capable of collecting and distributing energy to industrial users to reduce dependence on fossil fuels.

SSP also has potential to help solve other critical industrial and environmental issues. Clean, potable water becomes scarcer each day. The population of humans who live in regions with potential for water scarcity issues is expected to increase from 3.6 billion to between 4.8 and 5.7 billion by 2050.[23] The United States will face this issue as water shortages are expected to persist through 2050, primarily on the west coast.[24] SSP could be utilized to power extremely energy-intensive water desalination plants and newer atmospheric water generation systems[25] to expand the water supply, water treatment plants to reclaim more water, and hydroponic farming facilities (which use less water than traditional farms and irrigation). High energy consumption costs limit the widespread usage of water desalination. Desalination facilities generally spend over one-third of their budgets on energy to produce fresh water.[26] The facilities also produce greenhouse gases, contributing to environmental degradation. SSP would reduce their costs and emissions, further legitimizing the SSP industry as a means for clean water production.



TRANSPORTATION APPLICATIONS

Transportation accounted for approximately 26 percent of all U.S. energy consumption in 2020.[27] Of that energy production, 55.5 percent was consumed by light vehicles and 24.4 percent was consumed by commercial shipping trucks.[28] Electricity accounted for less than 1 percent of energy consumed by vehicles with the vast majority employing a variety of fossil fuels in 2020.[29] Space-based solar power will directly support the expanding use of electric personal vehicles,[30] commercial shipping vehicles and vessels, and transportation vehicles including buses, trains, and planes as those technologies develop and become mainstream over the next three decades. For scale, each typical 2 gigawatt SSP system could, for example, support an additional 4.5 million electric vehicles.[31] As gas stations are replaced by electric vehicle charging stations, new efforts will be required to collect and distribute power to the facilities. SSP provides a viable option, particularly to remote areas, supporting shipping trucks, which will likely become primarily autonomous and electric over the next three decades.

Transoceanic transportation can also benefit from SSP. Oceanic shipping supports 90 percent of trade and contributes approximately three percent of global carbon dioxide emissions.[32] The U.N. International Maritime Organization has set goals to reduce maritime shipping emissions by 50 percent by 2050.[33] The first fully electric, zero-emission shipping vessel launched in November 2021[34] and will be followed closely by models in development in Japan,[35] China,[36] and the United States.[37] Rectifying antennas could be in proximity to critical transportation hubs, including ports, so that SSP satellites could be used to power these vessels and the cargo trucks that move shipping containers inland to their destinations.

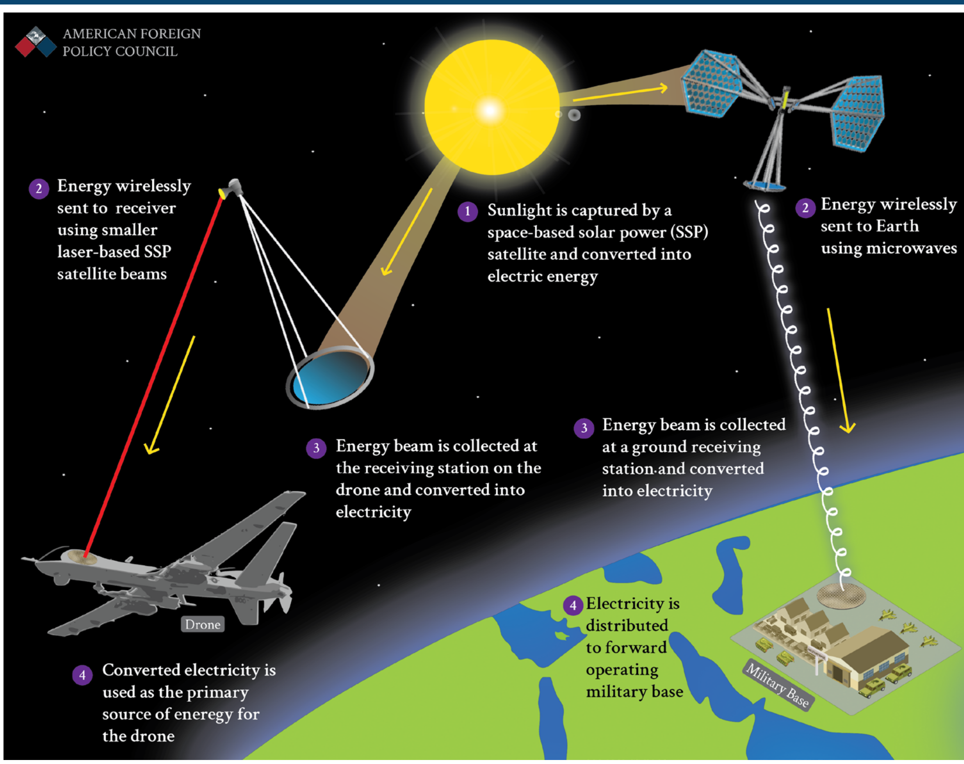
Similarly, rectifying antennas could be located near airports to power commercial and shipping aircraft as the electric aircraft market develops. Shipping aircraft account for approximately two percent of global carbon dioxide emissions.[38] Companies ranging from major plane manufacturers to tiny startups are working toward development of electric, emissions-free flight. Amazon, UPS, and many other major shipping companies are supporting these efforts.[39] The National Aeronautics and Space Administration (NASA) is also working with major plane manufacturers to develop sustainable, electric-power flight technologies.[40] While no electric cargo aircraft are currently flying, DHL placed the first order for fully electric cargo aircraft to launch their emissions-free shipping platform in 2024.[41] These orders will continue to grow in the short term and would benefit from energy provided by SSP satellites in the long term over the next three decades.

MILITARY APPLICATIONS

Space-based solar power represents a significant opportunity to revolutionize logistical support and power delivery for expeditionary military operations. The U.S. Air Force Research Laboratory's primary research effort related to SSP is supporting power delivery for expeditionary operations and forward operating bases. SSP satellites have the potential to provide power to remote installations including satellite communications stations, missile warning radar stations, research facilities, logistics facilities, airfields, and ports. The remote nature of some U.S. military bases, and of potential future forward operating bases, increases both the costs of transportation of fuel sources and the potential threats to those transport systems from hostile forces. SSP will circumvent both issues by providing power directly to forward forces and facilities.

Recent conflicts, such as Russia's invasion of Ukraine, demonstrate the coercive geopolitical power of hostile states interrupting global energy supplies, as well as the utility of having surplus energy supplies to counter adversarial coercion. The Russian invasion of Ukraine and the Nagorno-Karabakh war between Azerbaijan and Armenia demonstrate the extreme importance of fuel sources to prosecution of a war. They also demonstrate the extreme risk to command-and-control nodes, fuel and ammunition depots, and logistics operations from long-range precision fire assets such as cruise missiles, ballistic missiles, rocket and conventional artillery, as well as combat drones, loitering munition drones, and ground-attack aircraft. The Ukrainians have captured over 1,700 Russian military vehicles during the conflict thus far, many of which were abandoned after running out of fuel.[42] The Russians have also lost over 2,900 logistics and troop-carrying vehicles and three entire fuel trains.[43] These losses have dramatically restricted Russian operations in Ukraine and forced them to focus their operations in eastern Ukraine.

Figure 2. Space-based Solar Power Military Application



Source: American Foreign Policy Council and U.S. Department of Energy

The U.S. Defense Department was, prior to the conflict in Ukraine, working toward electrifying vehicles as a part of the department's overall focus on climate change. Operational planners and strategists are certainly considering the logistical failures of recent operations and the risks and costs of a force entirely dependent on fossil fuels. The department is prioritizing electrifying the entire fleet of 170,000 non-tactical vehicles.[44] The U.S. Army is moving toward hybrid electric replacements for key combat vehicles through the Next Generation Combat Vehicles program including the Bradley infantry fighting vehicle and the Abrams main battle tank.[45] The program, in line with programs across the Defense Department, is also working to develop electrically powered robotic combat vehicles to provide logistics and fire support.

Critical airborne intelligence and strike assets may also be powered by small laser-based SSP satellites. Current surveillance drones, including the Global Hawk (30+ hour endurance)[46] and Predator (27+ hour endurance),[47] must rotate with replacement drones in order to provide persistent surveillance over targets. Combining smaller military-focused SSP satellites with advanced drone technology presents an opportunity to fly surveillance assets with indefinite endurance over targets providing intelligence. SSP technology could support future drones as the United States replaces the retiring MQ-9 and RQ-4 with extreme-endurance, stealth ISR (intelligence, surveillance, and reconnaissance) platforms of the future. As electric aircraft technology advances, the future U.S. strategic bomber that will replace the upcoming B-21 Raider decades from now may also be an electric-powered drone, which would benefit from SSP and potentially fly indefinite strategic deterrence missions.

Country Programs

Table 2 summarizes SSP plans of China, Japan, the United States, and the European Union.

CHINA

China is developing space-based solar power to reduce dependence on fossil fuels, combat endemic pollution, reach carbon neutrality, provide energy security for the Chinese population and military, build influence with other states, and support the nation's long-term, strategic goals of global economic and military dominance. As a part of the Chinese plan to become a global power, President Xi Jinping announced his "Space Dream" in 2013 that China would become a world leading space power by 2045. In 2016, China announced the Space Information Corridor as a part of its Belt and Road Initiative, which seeks both to build goodwill with other countries and to increase the dependence of those countries on Chinese infrastructure and funding. Space Information Corridor projects are often dual-use, including the BeiDou GPS satellite constellation. Chinese SSP satellites would fulfill a similar dual-use role providing the People's Liberation Army (PLA) new domestically controlled capabilities, while supporting Chinese efforts to secure influence and build relations with other states and ensure their dependence on China for energy. SSP technology is a strategic imperative for China. The nation intends to dominate the field through a long-term, whole-of-government policy.

Within their current five-year plan, running from 2021 to 2025, the Chinese are working toward increasing renewable energy to 20 percent of their overall energy mix with a heavy emphasis on solar power. The language of the current plan suggests that the Chinese are making rapid progress. The 13th plan spoke of continuing renew-

Table 2. Space Solar Power Plans by Country (Testing and Energy Generation)

	Ground Test	Orbital Test	100 Kilowatt	1 Megawatt	100 Megawatt	1 Gigawatt
China	Active	None	2025	2028	2035	2050
Japan	Active	None	2025	2030s	2030s	2040s
United States	Active	Active	2025	No	No	No
European Union	None	None	No	2030	2035	2040
United Kingdom	2022-26	2027-31	2027-31	2027-31	2032-35	2036-39

able energy technology development, whereas the 14th plan focuses intently on rapidly expanding renewable energy platform installation. China has also announced plans to reach carbon neutrality by 2060.[48] In 2020, China relied on coal for 58 percent of its energy production and on oil for 20 percent, which caused massive amounts of carbon dioxide and particulate emissions.[49] The Chinese SSP program seeks to reduce dependence on fossil fuels over the next three decades.

The China Academy of Space and Technology (CAST), a subsidiary of the China Aerospace Science and Technology Corporation (CASC), proposed development of an SSP program in 2006. Subsequently, the China National Space Administration (CNSA) began research on SSP technologies in 2008. CNSA published a long-term road map for development of SSP in 2010. In 2013, President Xi received briefings on SSP research and proposals, which he approved in line with launching his Space Dream policy.[50] Chinese scientists, engineers, and academics created a nongovernmental organization, the SSPS Promotion Committee, to ensure collaborative efforts among organizations working on SSP. In 2019, the Ministry of Science and Technology began research on wireless power transmission for SSP power beaming. Also in 2019, the Chinese established a fully funded, state-run SSP prototype program.[51] Since 2006, Chinese SSP stakeholders have held regular symposiums on SSP technology development involving foreign delegations, including Russia, and have also attended foreign symposiums, expos, and workshops.

PLA Strategic Support Force (SSF) Space Systems Department involvement in the Chinese SSP program remains unclear. The PLA SSF is heavily involved in the Chinese space program at large, controlling the majority of space launches, space operations, space tracking and control, and space warfare.[52] The Chinese focus on dual-use technologies, the potential military applications of the technology, and PLA SSF control of the majority of space operations suggest the PLA is certainly monitoring SSP research efforts and is likely involved in those efforts.

The Chinese SSP program is rapidly expanding and currently conducting technology demonstration tests in Earth's atmosphere of complete power collection, beaming, and conversion systems. Two known major projects exist. The first project, established in 2018 in Xi'an by academics at Xidian University, is testing China's OMEGA SSP design and building an SSP development facility.[53] The project recently completed a rectifying antenna station. Scientists involved are currently testing microwave wireless power transmission from 300 meters off the Earth's surface with plans to test wireless power transmission from 20 kilometers in the near future.[54] The second project, established in 2018 in Chongqing by academics at Chongqing University, is testing wireless power transmission from airborne testing platforms to ground receivers and developing an SSP development facility.

The current SSP technology demonstrators are an early piece of the Chinese long-term SSP strategy. The future of the Chinese SSP program involves deployment of a 100 kilowatt demonstrator by 2025, a 1 megawatt demonstrator by 2028, a 100 megawatt satellite by 2035, and a commercial 1 gigawatt SSP satellite by 2050.[55]

To achieve these goals, the Chinese are developing massive-scale satellite component production, in-space servicing, assembly, and manufacturing (ISAM), in-situ resource utilization (ISRU), Lunar settlements, human spaceflight, and artificial intelligence technologies critical to SSP deployment. The Chinese space apparatus is planning to build factories on the Moon to exploit Lunar resources for building additional SSP satellites via additive manufacturing.[56] The Chinese are developing the Long March 9, a super heavy-lift rocket, and a reusable variant of the Long March 8 medium-lift rocket in order to support SSP satellite launch and construction.

The Chinese SSP program originally lacked government support due to cost, but the government is becoming increasingly supportive after the Chinese shift toward carbon neutrality by 2060.[57] The ever-present dangers of energy insecurity, pollution-related health problems, and environmental degradation have driven support for the SSP program. The Chinese will continue in their determined effort to be the first to achieve commercial-level SSP deployment to ensure energy security for their population, achieve energy market dominance, develop further influence over other states, and provide their military and space program with new capabilities.

JAPAN

Japan is developing space-based solar power to reduce the nation's dependence on nuclear power and fossil fuels and to provide energy security for the Japanese people and economy. The combination of geopolitical tensions and limited natural energy resources makes SSP a favorable option to fulfill Japanese energy needs. The

Japanese are seeking to increase renewable energy to 24 percent of their energy mix by 2030[58] and to 50 percent by 2050.[59] For Japan to successfully execute an SSP program, the Japanese Space Agency (JAXA) will likely have to deploy rectifying antennas in the ocean on oil rig–like platforms due to land constraints or will need to develop small-scale SSP platforms for specific applications.

JAXA initiated SSP technology research in the early 1980s. In 2014, JAXA release its long-term strategy for SSP. The Japanese are planning to launch a 100 kilowatt demonstrator, a 1 megawatt demonstrator, a 250 megawatt satellite, and a commercial gigawatt-level SSP satellite in the 2040s.[60] In March 2015, JAXA completed a significant microwave power beaming test on Earth to demonstrate the technical feasibility of the technology.[61] In December 2021, the Japanese government put forward a new basic space law that requires development of an SSP satellite demonstrator by 2025.[62] The nation is making progress toward long-term goals and a commercial SSP program. Japan will continue to develop SSP to provide power without reliance on nuclear and fossil fuels; to reduce pollution from coal, oil, and natural gas; and to improve on the intermittency of terrestrial solar power in Japan.

UNITED STATES

The current space-based solar power program in the United States is a series of loosely connected technology projects, demonstrators, and studies. The United States' interest in SSP began in the 1970s but has ebbed and flowed as political will and domestic interest have shifted. The Energy Research and Development Administration conducted a study in 1976 that projected an SSP program costing between $40 and $70 billion in research, development, test, and evaluation costs; $3.5 to $6 billion per gigawatt-level satellite; and a levelized cost of electricity of $0.30 to $0.50 per kilowatt hour of energy aimed at providing baseload power for terrestrial energy markets.[63] Several congressional hearings were held during the late 1970s, which resulted in minimal funding and support for conducting limited SSP research.

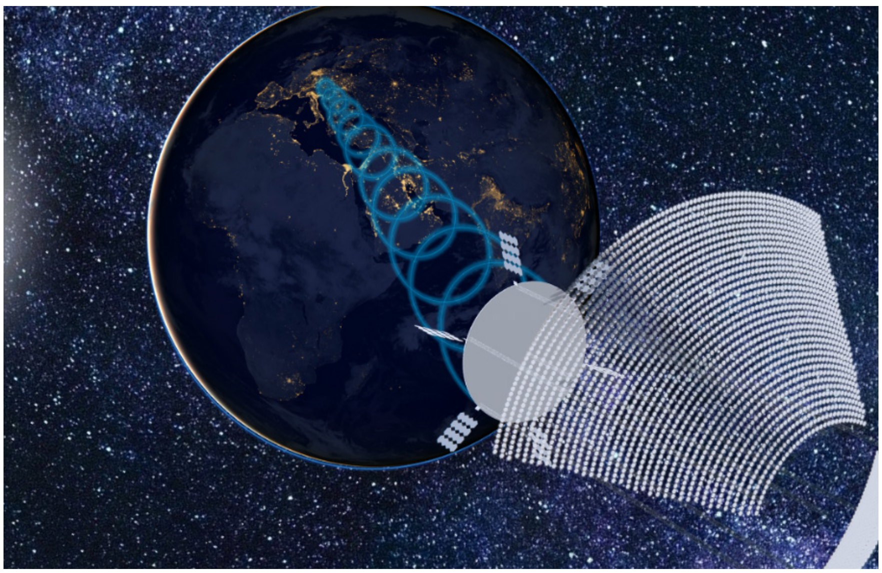
NASA conducted a study between 1995 and 1997 to determine whether SSP had become more economically and technologically feasible. NASA conducted an additional study during 1998 to define SSP concepts as a part of the SSP Exploratory Research and Technology program, which led to the 2001 SSP Technology Advanced Research and Development program focused on research to advance wireless power transmission and gigawatt-level SSP satellites. The studies were not supported adequately with legislation and funding, and did not result in development of an SSP program. They did, however, suggest the technical and economic feasibility of such a program. In 2007, the Defense Department conducted an internal study through the National Security Space Office, which showed the technical and economic feasibility and recommended the development of a national SSP program.[65]

NASA conducted the most recent U.S. study in 2012, which resulted in the SPS-ALPHA satellite model that would provide electricity at an expected cost of $0.09 per kilowatt hour.[66] In the decade since the study, the SPS-ALPHA model study has been updated several times to the SPS-ALPHA Mark III, which the study expects to provide electricity at approximately $0.06 per kilowatt hour.[67] The Mark III model satellite is expected to cost $8 billion, operate in geosynchronous Earth orbit (GEO), and provide 2 gigawatts of energy. The study provides a path for launch of such a platform in the 2030s and up to 50 satellites by 2050, providing 100 gigawatts of energy. NASA is currently conducting a short-term study of the feasibility of an SSP program with modern technology in response to the current push for solutions to ongoing climate change and energy insecurity.[68]

Over the decades since the 1970s, 37 U.S. states have implemented renewable portfolio standards; 14 of those states are working toward producing 50 percent or more of their energy through renewable energy sources.[69] Until September 2021, the United States had no national strategy or goals for renewable energy. Within the Department of Energy's September 2021 Solar Futures Study, the Biden administration announced national goals to produce 40 percent of the nation's electricity via solar energy by 2035.[70] In 2020, the United States installed 15 gigawatts of solar energy collection, bringing the United States' total to 76 gigawatts or 3 percent of total U.S. electricity production. To reach 40 percent of the United States' electricity production by 2035, the Energy Department estimates that the United States will need to quadruple solar power installation and reach 1,000 gigawatts of solar energy.[71] Further, according to the Energy Department, the United States has the potential to reach 1,600 gigawatts by 2050, with wind and solar accounting for 90 percent of that electricity production, a carbon-free electrical grid, and a carbon-free national energy system that includes major industries.[72]

The Solar Futures Study demonstrated that expansion of solar power will directly create between 500,000 and 1.5 million jobs by 2035. The economic benefits of job creation will be supplemented by dramatically reduced pollution leading to health and environmental cost savings estimated at between $1.1 and $1.7 trillion, far offsetting the costs of research and development.[73] Should SSP be included, these numbers will likely increase.

Figure 3. SPS-ALPHA Satellite Model



Source: SPS-ALPHA concept and graphic provided courtesy John C. Mankins.

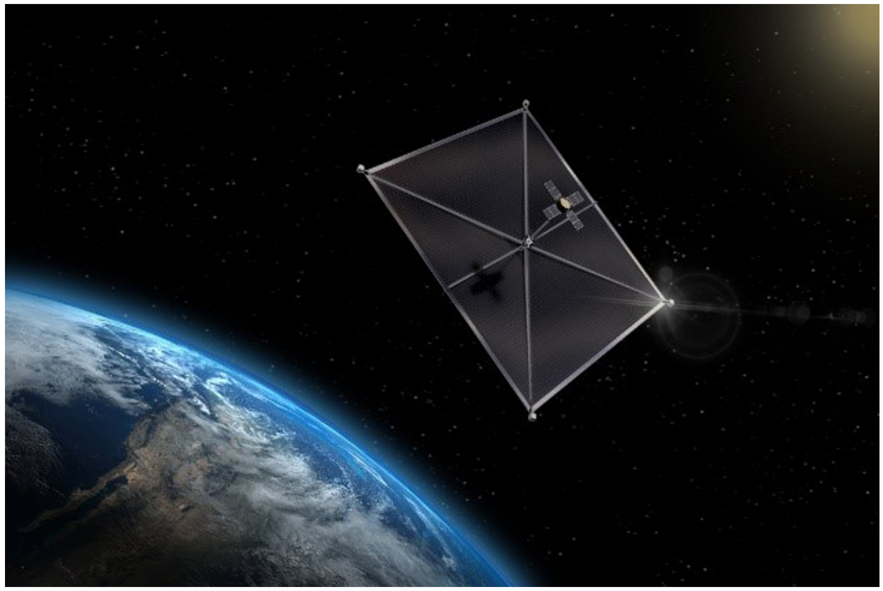
Private industry has recently taken note of the potential of SSP, signaling the possibility of private investment as well. CITI Group's research arm included estimates of SSP in its review of growing space industries, predicting revenues from SSP might reach $23 billion by 2040.[74]

While NASA has begun a short-term study of SSP potential,[75] and the Energy Department has experimented with SSP, the Defense Department remains the primary current promoter of the technology. The U.S. Space Force X-37B space plane is currently flying a U.S. Navy experiment, the Photovoltaic Radio-Frequency Antenna Module (PRAM), which is testing solar power collection and microwave conversion in space conditions.[76] The U.S. Air Force is executing the Space Solar Power Incremental Demonstrations and Research Project (SSPIDR).[77] SSPIDR consists of three projects. The Space Power Infrared Regulation and Analysis of Lifetime (SPIRAL) will launch to the International Space Station in 2023 to test thermal management of SSP technology and materials. The Space Solar Power Radio Frequency Integrated Transmission Experiment (SSPRITE) will test solar power collection, conversion to radio frequencies, and beaming capabilities. The Space Power Incremental Deployables Experiment (SPINDLE) will test the structures and deployment methods to best support SSP arrays in space.[78]

The Air Force Research Laboratory (AFRL) and Naval Research Laboratory (NRL) face resource shortfalls that are preventing rapid and expansive research and development. Both organizations are making incredible technological progress toward SSP capabilities but require permanent funding to improve research efforts, particularly to compete with the Chinese. Legislation providing for a permanent national SSP program with appropriate funding and a definitive home for defense-focused SSP research will be greatly beneficial to future commercial, civilian, and military SSP programs just as prior GPS and communications satellite programs originally focused on military applications have been. Current AFRL technology demonstrators that will compete with Chinese tests are not fully funded and are subject to cancellation. AFRL is planning for successively more powerful demonstrators in 2025 and 2030 should they receive adequate funding. The projects are making major progress, including recent successes in wireless power transmission.[79] These efforts must be protected in the long term to compete with China.

Despite these programs, the most recent National Space Policy, from the Trump administration, makes no mention of SSP,[80] and the Biden administration has not released a policy. The Biden administration released a Space Priorities Framework in December 2021,[81] which makes no mention of specific technology development including SSP but does highlight key areas that SSP development could directly support. The framework puts forth benefits from expansion of the American space industry, including enabling the human way of life, creating STEM jobs, driving innovation, managing natural resources, combating climate change, and inspiring the American people. SSP satellites can provide all of these benefits. The framework also focuses on deepening international space partnerships and providing national security–focused capabilities. SSP gives the United States the chance to lead as the country has with GPS and satellite communications, the chance to collaborate with U.S. allies and partners for the betterment of the planet, and a variety of military and space capabilities that will support national security objectives. SSP further provides the opportunity to work toward the Biden administration's priorities of maintaining global leadership in space, developing the American commercial space sector, and investing in future American STEM experts.

Figure 4. The Air Force Research Laboratory's Space Solar Power Incremental and Demonstrations Research Project



The image depicts AFRL's Space Solar Power Incremental and Demonstrations Research Project beaming solar power from space to earth. SSPIDR consists of several small-scale flight experiments that will mature technology needed to build a prototype solar power distribution system. (Image by AFRL) Source: https://afresearchlab.com/technology/space-power-beaming/.

EUROPEAN UNION

The European Union (EU) is currently expanding efforts in pursuit of a space-based solar power program, supporting its overall plan to achieve carbon neutrality. The EU is working to increase overall renewable energy mix to 38.5 percent by 2030 with an emphasis on implementation of clean energy–powered electric cars and commercial shipping and transportation vehicles.[82] Further, the EU is planning to reach carbon neutrality by 2050.[83] The European Space Agency solicited technological concepts and satellite designs for its SSP program in 2021.[84] The ESA selected 13 projects from space companies, startups, and academic institutions for funding to advance SSP.[85] These projects will provide the basis for a future commercial program.

The ESA believes that SSP can provide a flexible and reliable energy source to support the EU's commercial and industrial energy consumption needs and future space colonies.[86] The agency's current goals include launching a commercial SSP satellite array to support the EU's energy needs and to combat environmental degradation.[87] The ESA has not released a long-term strategy for launching technology demonstrators and SSP satellite arrays. Should the ESA implement an SSP satellite array, the power provided will not only help decarbonization but also reduce energy dependence on Russia and the Middle East, removing key geopolitical and economic weapons of potentially hostile adversaries. Domestic energy production that offers energy security via a clean renewable source will give the EU greater flexibility on the international stage and support overall decarbonization goals. In August 2022, the ESA released two favorable cost-benefit analysis studies, and the ESA director has announced an intention to ask ESA member states to provide significant funding for a development project they call Solaris.[88]

OTHER COMPETITORS

Several states are revitalizing or initiating space-based solar power programs. The Soviet Union began research on SSP in 1987 with the intent to develop the program over decades.[89] After the collapse of the Soviet Union, the Russian Federation maintained interest in SSP and is continuing research to achieve a viable system.[90] India initiated research on SSP in 1987. India's space agency, the Indian Space Research Organisation, continues to conduct studies and research on SSP.[91] The United Kingdom expressed interest in SSP, launching a study in November 2020 to explore the safety and reliability of an SSP system. The United Kingdom has initiated a Space Energy Initiative (SEI),[92] which is aiming to launch an SSP satellite array by 2050 in efforts to help decarbonize.[93] The report, released in September 2021, concluded that SSP is technically and economically feasible and that the technology would bring significant economic and environmental benefits to the United Kingdom, provide energy at reasonable levelized costs of electricity, and help the United Kingdom to reach its overall net-zero goals.[94] In response to growing concerns about dependence on Russian energy, the U.K. government announced $3 million in funding for SSP development.[95] Australia is also pursuing SSP via a joint venture with the United States called Solar Space Technologies. The venture aims to put the first commercial SSP satellite demonstrator in orbit by 2027.[96] These programs present opportunity for collaboration as well as potential competition to dominate energy markets.

Challenges

Space-based solar power is a potentially game changing technology, but the technology is not without challenges and limitations, as summarized in Table 3.

ENVIRONMENTAL IMPACT

One commonly expressed concern is the potential of microwave beaming to cause atmospheric heating. The expected power levels at which SSP operates are near levels that might possibly cause ionospheric modification.[97] SSP beams could heat the ionosphere to the point of shifting plasma density, which will affect how radiofrequency signals interact and pass through.[98] This could also shift the chemical balance of the atmosphere. U.S. studies demonstrate that SSP beam heating of the atmosphere would be negligible and cause vastly less heating relative to coal, oil, natural gas, and nuclear plants that deliver similar power levels, with none of the particulate or greenhouse gas emissions of coal, oil, and natural gas.[99] SSP microwave

Table 3. Space-based Solar Power Challenges

Space-based Solar Power Challenges	
Environmental Challenges	SSP beams could heat the ionosphere, but multiple U.S. studies demonstrate that SSP beam effects would be negligible relative to fossil fuels
Human Health	SSP will operate in lower-energy, nonionizing microwave wavelengths, more akin to WIFI and cellular wavelengths Additional study of SSP wireless power beaming should be conducted. Safety standards must be updated to include regulation of SSP wireless power beaming
Launch Costs and Capabilities	The development of reusable heavy-lift space launch vehicles (SLVs) and their cost per launch have historically prevented the economic viability of space solar power Low-cost super heavy heavy-lift platforms including NASA's Space Launch System (SLS) or SpaceX's Starship are necessary to launch SSP satellites into GEO orbits
Satellite Construction	Construction costs for development of space construction technologies and spacecraft, production of satellite components and rockets on Earth, and the assembly of satellites in orbit, are expected to range in the tens of billions of dollars for SSP satellites Once satellite components are in space, robotic construction technologies will become critical to the success of an SSP program
Orbit and Frequencies	Any country deploying satellites must coordinate with the international community for orbits and frequencies to avoid electromagnetic and orbital interference and collisions
Supply Chain and Critical Minerals	Resourcing rare earth elements (REE) and other critical minerals will become a challenge, primarily due to Chinese dominance of mining and processing of the mineral, however, a number of critical minerals are available on the Moon

beams are not expected to be refracted or absorbed at higher rates due to ionospheric heating.[100] SSP effects are mitigatable with appropriate legislation and power beaming protection standards.

HUMAN HEALTH

The public may also be concerned that microwave radiation may present a risk as various forms of radiation can cause organ failure or cancer, or could negatively impact reproductive system health. Most of these fears arise from well-studied effects of ionizing radiation, which are conclusively proven to be dangerous to human health. In sharp contrast, space-based solar power will operate in lower-energy, non-ionizing microwave wavelengths, more akin to Wi-Fi and cellular wavelengths.

While the health effects of non-ionizing radiation remain an area of active study, specific fears that microwave radiation could cause cancer in humans are not supported by the evidence. Studies from the American Cancer Society indicate that, under international microwave radiation exposure limits, there is no clear increase in risk of cancer.[101] Studies from the U.S. Food and Drug Administration also show insufficient evidence to link microwave radiation to cancer.[102] The National Toxicology Program, a subordinate of the National Institutes of Health (NIH), does not include microwave radiation in the organization's annual report on carcinogens produced for Congress.[103]

The public and responsible policymakers must also be sensitive to any potential effects of non-ionizing radiation on reproductive health. Reports from NIH, the Centers for Disease Control and Prevention, and other organizations generally agree on the possibility that non-ionizing radiation could negatively affect reproductive health and fertility of men and women, but these reports provide no direct links, as they do with ionizing radiation.[104]

These studies look at microwave radiation in general and have not considered future SSP programs. The 1980s Energy Department evaluation of SSP did extensive health and environmental evaluation[105] —including the sponsorship of three studies of the effects of SSP frequency microwaves on bees, birds, and small mammals—and no significant effects were observed. [106] Nevertheless, additional study of SSP wireless power beaming should be conducted to ensure the safety of the satellites. Safety standards must be updated to include regulation of SSP wireless power beaming.

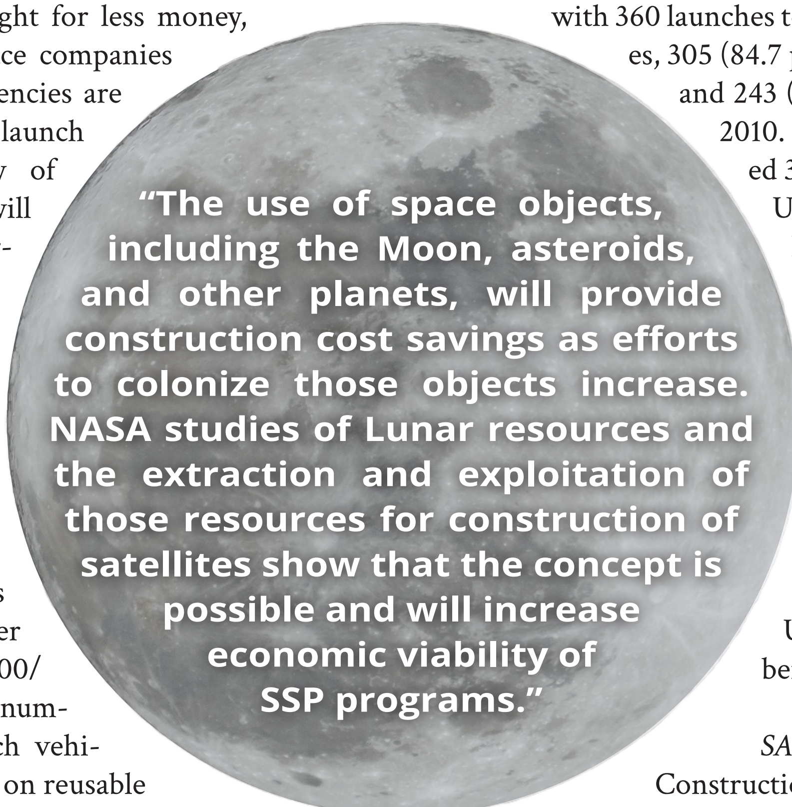
At present, the U.S. Federal Communications Commission (FCC) combats the threat of excessive microwave exposure by providing strict limits for human exposure to radiation, requiring environmental studies for microwave-emitting facilities, and monitoring microwave-emitting technologies—though wireless power transmission lacks definitive regulation and policy.[107] The American National Standards Institute (ANSI) and Institute of Electrical and Electronics Engineers (IEEE) also publish standards and practices related to human exposure to microwave radiation.[108]

Extending such safety and industry standards provides a viable way forward to deal with potential SSP health risks. SSP radiation is mitigatable through measures including buffer zones around receivers, microwave absorbing panels at receivers, and radiation exposure legislation mandating power levels, exposure times, and SSP receiver locations. In current tests in Earth's atmosphere, the Chinese are mitigating microwave radiation via buffer zones and microwave shielding to prevent accidental exposure or overexposure.[109] With proper legislation, funding, and technology, SSP satellites and receivers can operate safely without impact to human health.

LAUNCH COSTS & CAPABILITIES

The development of reusable heavy-lift space launch vehicles (SLVs) and their cost per launch have historically prevented the economic viability of space-based solar power. Launch costs per kilogram (kg) of payload have fallen sharply since the 1970s. SpaceX's Falcon 9 now launches 22,800 kg at $62 million per flight ($2,700/kg) and the Falcon Heavy launches 63,900 kg at $90 million per flight ($1,400/kg).[110] Compared in modern dollar values to earlier U.S. programs, including the Titan ($32,000/kg), the Atlas ($28,000/kg), and the Space Shuttle ($61,700/kg), reusable rockets demonstrate significant savings.[111] Russia,[112] China,[113] the European Space Agency,[114] India,[115] and American companies Rocket Lab[116] and Relativity Space[117] are all developing reusable SLV prototypes in conjunction with SpaceX's Falcon 9 variants and the upcoming super heavy-lift Starship. These reusable SLVs will reduce costs across the space launch market, improving economic viability of space asset delivery.

Despite SpaceX's success with the Falcon 9 and other upcoming reusable variants, they demonstrate only the feasibility of low-cost, reusable space flight. An SSP program will also require low-cost launch support from super heavy-lift platforms such as SpaceX's Starship to put satellites into geosynchronous Earth orbit (GEO), increasing costs significantly compared to launches to low Earth orbit. Additionally, some initial development might be supported by NASA's Space Launch System (SLS). The SLS Block 1 is expected to support launches to the Moon carrying 27,000 kg at $2 billion per launch ($74,000/kg).[118] SLS Block 2 cargo missions are expected to carry 46,000 kg, further reducing costs.[119] SpaceX's Starship is expected to carry 21,000 kg without orbital refueling and more than 100,000 kg with orbital refueling to GEO and the Moon.[120] Starship is designed to be reusable, further reducing launch costs. In addition of carrying more weight for less money, the private-sector space companies and national space agencies are currently outpacing launch demand with supply of launch vehicles and will continue to do so. Current SpaceX goals include scaling Starship production to enable them to put into orbit one to ten million metric tons in a single year,[121] and to use a high volume of launches to drive costs down to $10 million per Starship sortie, or $100/kg.[122] Production and number of available launch vehicles, with an emphasis on reusable platforms, will not prevent the construction of an SSP array.



Over the next three decades, as SSP programs are implemented, super heavy-lift launch SLV technology and manufacturing will advance to support SSP and Lunar and Martian settlements and will reach economies of scale at which current medium-lift reusable platforms are manufactured and supporting regular launches. The competition between the United States and China for the space launch market and the development of reusable and heavy-lift platforms is also relevant to the future of SSP programs. The numbers below are approximate but demonstrate Chinese determination to achieve dominance.

NASA conducted the United States' first launch in 1958. Over the next 63 years, the United States averaged 26.1 orbital launches per year with 1,650 launches total. Of those launches, 427 (or 25.9 percent) occurred after 2000. Of the United States' total launches, 266 (16.1 percent) occurred after 2010. In 2020, the United States conducted 44 orbital space launches.[123] The U.S. space program has decelerated over time, with spikes in the 1960s, 1990s, and 2010s, in addition to a spike in 2020–2022 in an effort to compete with a rising Chinese program.

The China National Space Administration conducted the PRC's first orbital space launch in 1971. Over the next 50 years, China averaged 7.2 orbital launches per year with 360 launches total. Of China's total launches, 305 (84.7 percent) occurred after 2000 and 243 (67.5 percent) occurred after 2010. In 2020, the PRC conducted 35 orbital space launches and U.S. Space Force ISR Director Brigadier General Gagnon says China now has 600 satellites in orbit which "connect to their weapons systems at greater and greater range."[124] Chinese space launches have accelerated rapidly under the leadership of President Xi and are approaching the United States' launch numbers.

SATELLITE CONSTRUCTION

Construction costs, including development of space construction technologies and spacecraft, production of satellite components and rockets on Earth, and the assembly of satellites in orbit, are expected to range in the tens of billions of dollars total for a space-based solar power satellite array. While SSP satellites were previously economically prohibitive due to research and development costs, new advances demonstrate the potential for massive-scale SSP construction efforts.

SpaceX's Starlink spinoff has demonstrated the capacity for large-scale satellite manufacturing, producing more than 120 satellites per month.[125] China is operating several satellite facilities capable of producing hundreds of satellites a year, with more facilities being constructed.[126]

Space agencies and space companies are repetitively manufacturing the same satellites in high numbers at decreasing costs. Applying repetitive manufacturing methods to SSP satellite components will increase the economic feasibility of such a program.

Once satellite components are in space, robotic construction technologies will become critical to the success of an SSP program. Maxar, in partnership with NASA, is currently developing the Space Infrastructure Dexterous Robot (SPIDER), which will be attached to Maxar's OSAM-1 spacecraft (On-Orbit Servicing Assembly and Maintenance). The OSAM-1 will assemble satellites in orbit and provide maintenance on satellites.[127] The NASA program could be scaled and applied to support SSP programs in the future. DARPA's Novel Orbital and Moon Manufacturing, Materials and Mass-efficient Design (NOM4D) program is also developing technologies for orbital and Lunar construction and manufacturing.[128] Within NOM4D, DARPA is working on the Robotic Servicing of Geosynchronous Satellites (RSGS) program to develop spacecraft with robotic arms capable of constructing and maintaining satellites in GEO where SSP satellites would operate.[129]

DARPA is competing directly with China's CASC, which is also studying and developing robotic orbital assembly spacecraft.[130] The Chinese are known to have launched and are currently operating co-orbital satellites with capabilities to interact with and change trajectories of other space objects, as demonstrated earlier this year with Shijian-21.[131] Chinese co-orbital satellite technology, in conjunction with artificial intelligence and robotics technology, will be able to assemble satellites in orbit.

The use of space objects, including the Moon, asteroids, and other planets, will provide construction cost savings as efforts to colonize those objects increase. NASA studies of Lunar resources and the extraction and exploitation of those resources for construction of satellites show that the concept is possible and will increase economic viability of SSP programs. The Chinese conducted similar studies with similar results, concluding the possibility of using Lunar resources to construct satellites.[132] The concept is a key part of China's long-term SSP strategy. Space mining of the Moon, asteroids, and other planets will provide the necessary resources to construct SSP satellites as well as both mass drivers and rocket fuel for launches to put the satellites into orbit. The combination of abundant resources to build SSP satellites and lower gravity vastly reducing launch costs would allow SSP programs to expand more rapidly.

ORBITS AND FREQUENCIES

Satellite orbits and electromagnetic frequencies are finite resources managed by the International Telecommunication Union (ITU). The ITU puts out guidance to its 193 member states on international frequency management and sharing through Radio Regulations. These regulations are updated every three to four years through conferences involving the majority of member states, hundreds of private-sector companies, and telecommunications organizations.[133] The ITU maintains the Master International Frequency Register (MIFR) and is responsible for over 2.6 million terrestrial and 1.1 million space service frequency assignments as well as tens of thousands of space orbits for satellites supporting global telecommunications and government applications.[134] An additional 350,000 satellite broadcast service and 25,000 satellite fixed service frequencies are for future uses.[135] Any country deploying space-based solar power satellites must coordinate through the ITU with the international community for orbits and frequencies to avoid electromagnetic and orbital interference that could disrupt services and cause satellite collisions.

International cooperation and compliance with international space treaties and principles will be critical to legitimately secure resources and ensure international support. Once a state acquires the rights to operate within a frequency, the state is responsible for providing licenses to end users. The FCC manages electromagnetic frequencies for nongovernment usage while the National Telecommunications and Information Administration (NTIA) manages government usage.[136] Military SSP satellite operators will coordinate with the NTIA for frequencies, while private-sector operators will coordinate with the FCC for frequencies. Domestic and international support for an SSP program will remain critical. Without access to finite frequencies and orbits, an SSP program will be untenable.

SUPPLY CHAIN & CRITICAL MINERALS

Resourcing rare earth elements (REE) and other critical minerals will become the greatest challenge for space-based solar power and for the defense and aerospace sectors in general in the coming decades primarily due to Chinese dominance of mining and processing of the minerals. The U.S. Geological Survey (USGS) reviews and publishes a list of "critical minerals" encompassing REEs, source minerals, and minor metals, among other minerals that the U.S. economy is highly dependent on and reliant on imports for, that are threatened by supply chain issues, and that are based on supplier willingness to continue supporting the United States.[137] The 2022 list included 50 critical minerals that China and a limited number of other states control the mining and processing of.

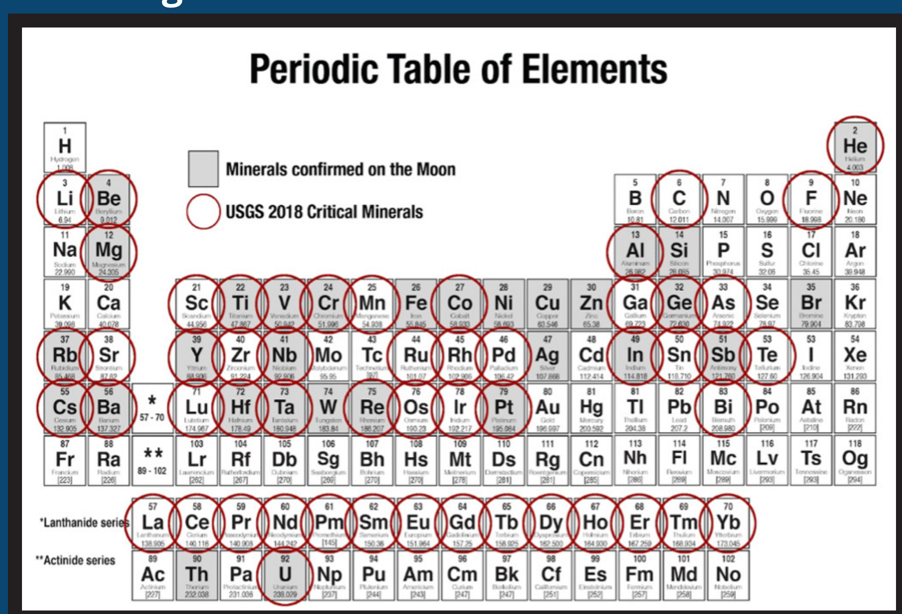
The United States is reacting to the threat, but reigniting the U.S. REE and critical mineral sector will take years, massive financial support, and the willingness to pollute. The United States dominated global REE and critical mineral mining and refining between the 1960s and 1980s.[138] During the 1980s and 1990s, the dual phenomena of dramatically increasing Chinese demand for such minerals and growing American interest in environmental responsibility—which pushed mining and processing out of the United States—led China to dominate the industry. Approximately 85 percent of REE mining and 95 percent of REE refining and processing is done in China.[139] China is also heavily invested in other critical minerals and materials but controls less market share.

The United States mines some of the 17 REEs and other critical minerals but sends those minerals abroad for refinement and imports 100 percent of refined REEs. While several potential mines exist in Wyoming, Texas, Alaska, and elsewhere, only one rare earth element mine is operational in California.[140] Of the U.S.-defined critical minerals, 100 percent of the supply of 17 are imported, 75 percent of the supply of 22 are imported, and 50 percent of the supply of 11 are imported, placing extreme reliance on foreign suppliers including China and Russia.[141]

The majority of the 17 REEs are used in space and renewable energy components. Satellite components remain dependent on aluminum, chromium, cobalt, copper, magnesium, molybdenum, nickel, silicon, titanium, and vanadium, among other critical minerals.[142] These components support the production of semiconductors, lasers, sensors, and aerospace alloys. Photovoltaic panels are dependent on rare earth and critical minerals, including arsenic (U.S. imports 100 percent), gallium (U.S. imports 100 percent), germanium (U.S. imports over 50 percent), indium (U.S. imports 100 percent), and tellurium (U.S. imports over 75 percent).[143] Batteries supporting solar energy collection are dependent on critical minerals including cobalt (U.S. imports over 60 percent), graphite (U.S. imports 100 percent), lithium (U.S. imports over 50 percent), and manganese (U.S. imports over 50 percent).[144]

This problem is not specific to SSP. Defense, aerospace, transportation, information technology, and many other industrial sectors will be affected by supply chain issues with an emphasis on critical minerals should the Chinese decide to act as they did in 2010 and impose export restrictions. The U.S. government must implement policy to restart domestic processing and to diversify the supply chain for critical industries. Of note, in an interesting linkage to both Lunar ISRU plans and ISAM potential, NASA Ames Commercial Space Portal has identified that a number of USGS-identified critical minerals are confirmed to be available on the Moon.[145]

Figure 5. Periodic Table of Elements



Source: Lynn D. Harper, NASA Ames.

Conclusions

The country that successfully implements the first commercial space-based solar power satellite array will profit economically,

militarily, and geopolitically over its adversaries, neighbors, and the global energy market. Currently, China is the state most likely to achieve that goal. The PRC is implementing a long-term SSP strategy nested within larger goals of becoming a global space power by 2045 and a global economic and military power by 2049. Should China succeed, it will wield significant influence over the international energy market and those states dependent on Chinese energy supply, and China will use that influence to support its long-term strategy for global dominance. China will gain energy security, protecting the country from geopolitical battles over energy and resources. The nation will drive its economic growth in a sustainable manner and reduce emissions in the process, meeting international goals over the next three decades. The Chinese government will expand the capabilities of its expeditionary military forces and space exploration program. China has the political will, the scientific prowess, and the funding to execute an SSP program at a commercial level within the next three decades.

The creation of an incredibly expensive, decades-long project is most susceptible to shifting political will and domestic interest, not technical or economic feasibility. Studies have shown that SSP has the potential to provide energy at an acceptable levelized cost of electricity, and current research and development efforts have proved that SSP satellites will work. These studies and research efforts have, however, lacked a dedicated long-term strategy, legislation, and funding.

The United States must execute a series of legislative and policy actions to support the U.S. space community's efforts to compete with China over this key technology. The executive branch must coordinate to produce a new National Space Policy that incorporates SSP technology development and a national SSP program. That policy will require supporting legislation that will provide permanent status and funding for a national SSP program and assign government agencies and departments SSP-related missions. The policy and legislation must define which government agency is in charge of the overall effort. Additional studies and legislation must be conducted and put in place to ensure the safety of SSP operations.

Future SSP satellite arrays must also be incorporated into other U.S. efforts by the defense, cyber, and intelligence communities as they will be vulnerable to anti-satellite missiles, cyberattacks, electronic warfare, and espionage. These stakeholders must work together to ensure that SSP satellites can operate safely within their orbits.

Stakeholder government agencies from the economic and foreign policy communities must also work together to create a permissive international environment, ensuring orbits and frequencies through which U.S. SSP satellites can operate and favorable domestic and international markets for SSP providers to distribute energy. Should a commercial-level SSP program develop, hundreds of thousands of STEM and energy jobs will be created. The industry will in turn create revenue for U.S. companies and the U.S. government.

Most importantly, SSP will provide clean, renewable energy that will support the transition away from polluting fossil fuels to support combating atmospheric-heating-based climate change, environmental degradation, and energy insecurity and to support global sustainable development.

Recommendations

National Security Council

- ★ Develop a new National Space Policy that incorporates SSP technology research and development and the implementation of a permanent national SSP program to compete with China. The policy should provide definitive milestones including a full technology demonstrator in orbit by 2030 and commercial gigawatt-level satellites in orbit providing energy by 2050. The policy should incorporate cooperation with partners and allies.
- ★ Coordinate the implementation of SSP policy and strategy within the larger national security apparatus and with stakeholder government agencies and departments.

National Space Council

- ★ Conduct an assessment in coordination with NASA, the Defense Department, the Commerce Department, and other critical stakeholders of a future national SSP program with civilian, military, and commercial applications that will compete with China's program and timeline.
- ★ Provide SSP research, development, implementation, and funding policy recommendations to the president and the National Security Council in coordination with involved stakeholders.

- Synchronize U.S. civilian, military, and commercial SSP research, development, and deployment in accordance with the National Space Policy.
- Coordinate the implementation of SSP policy and strategy, SSP information sharing, and cooperation between SSP stakeholder government agencies and departments.

Office of Science and Technology Policy

- Publish a national Space Solar Power Strategy and Action Plan that enumerates national-level goals and clearly communicates national intent.
- Publish an executive order and implementing guidance that provides clear roles and tasks for key agencies.

Congress

- Pass legislation to mandate a permanent SSP program with appropriate funding for ongoing and future research and development efforts within the government (Defense Department, Energy Department, NASA), private sector, and academic institutions.
- Pass legislation assigning the U.S. Space Force responsibility for the defense of all U.S. SSP satellites and the operation of U.S. military SSP satellites.
- Pass legislation assigning NASA responsibility for the operation of U.S. civilian government SSP satellites
- Pass legislation to encourage development of a commercial SSP satellite and electricity industry and supporting the private-sector industrial base.
- Pass legislation to restart the American critical mineral and rare earth metal mining and refining industries to reduce dependence on China, such as the REEShore Act currently in committee.
- Pass legislation assigning the FCC responsibility to conduct a study of SSP wireless power transmission microwave exposure limits to update safety standards and provide methods for compliance for future power beaming.
- Pass legislation to authorize and encourage microwave frequency band allocation for SSP satellite beaming and authority to establish standards (with industry input) for microwave beam exposure for the safety of receiver antenna workers, the areas surrounding receiver antennas, aircraft, and other entities in close proximity.

National Aeronautics and Space Administration

- Establish a Space Solar Power Office to manage NASA's SSP research portfolio.
- Pursue research and development of ISAM technologies and SSP technology demonstrators.
- Continue to pursue development and testing of the Space Launch System and variants for super heavy-lift missions including SSP satellite component launch
- Develop a subordinate organization, infrastructure, and doctrine to operate, track, and maintain government civilian SSP satellites and terrestrial receiver antennas
- Publish an annual report to Congress, the National Economic Council, and the National Space Council on the national SSP program and civilian research and development efforts.

Department of Energy

- Establish a Space Solar Power Office to manage the Energy Department's SSP research portfolio.
- Pursue research and development of photovoltaic, power generation, heat dissipation technologies, and SSP technology demonstrators.
- Engage in SSP technology transfer to the U.S. private sector to encourage development of a commercial SSP industry.
- Publish an annual report to Congress, the National Economic Council, and the National Space Council on SSP-focused research and electricity generation and distribution applications.

Department of Defense

- Pursue defense-related SSP research through subordinate organizations to advance microwave and laser power beaming technologies and megawatt-level technology demonstration satellites in the short term, working toward larger platforms.
- Publish an annual report to Congress and the National Space Council on SSP research progress toward military utility of SSP for powering expeditionary operations and other functions.

United States Air Force and Air Force Research Laboratory

- Continue to pursue and expand ongoing mission-focused SSP research through the SSPIDR program to advance solar energy collection technology, microwave and laser conversion technologies, and microwave and laser beaming technologies.

- ★ Complete research and development of and launch an initial technology demonstrator satellite to show feasibility of supporting future mission sets, including powering forward operating bases and expeditionary capabilities by 2025.
- ★ Continue research and development of larger scale technology demonstrators for deployment and testing by 2030.

United States Navy and Naval Research Laboratory

- ★ Continue to pursue and expand ongoing mission-focused SSP research through the PRAM program and flight tests via orbital test vehicle missions to advance the technical maturity of solar energy collection, microwave and laser conversion technologies, and microwave and laser beaming technologies.

United States Space Force

- ★ Develop units, infrastructure, and doctrine to operate, track, and maintain military SSP satellites and to defend all commercial, civilian government, and military SSP satellites.
- ★ Coordinate with the U.S. Navy and U.S. Air Force to incorporate research and development efforts into future SSP efforts.

United States Space Force SpaceWERX

- ★ Expand the Orbital Prime effort within Space Prime Initiative to accelerate ISAM technology development for SSP satellite construction and support through partnerships with private-sector companies and academic institutions.
- ★ Develop a Solar Prime effort within the Space Prime Initiative to accelerate SSP technology development for SSP satellite research and development through partnerships with private-sector companies and academic institutions.
- ★ Launch an SSP-focused Hyperspace Challenge through the Space Ventures initiative to build collaboration with startups and accelerate SSP-related technology development.

Defense Advanced Research Projects Agency

- ★ Continue to pursue and expand ongoing ISAM technologies, which will be critical for SSP satellite construction.
- ★ Continue to pursue and expand artificial intelligence and robotic construction technologies that will support SSP satellite array development in geosynchronous Earth orbit (GEO).

Department of Commerce

- ★ Establish a Space Solar Power Office to manage the Commerce Department's SSP portfolio and to conduct commercial liaison with private-sector firms.
- ★ Publish an annual report to Congress, the National Economic Council, and the National Space Council on required policies, legislation, and incentives required to advance grid parity commercial SSP.
- ★ Provide recommendations to Congress, the National Economic Council, and the National Space Council on structuring of public-private partnerships with NASA, the Defense Department, the Energy Department, and other associated stakeholders to encourage development of a self-sustaining commercial SSP industry.
- ★ Liaise with private-sector defense contractors, aerospace component manufacturers, photovoltaic component manufacturers, energy and aerospace technology startups, and space launch providers conducting SSP relevant research and development.

Department of State

- ★ Coordinate with the U.N. Office for Outer Space Affairs, International Telecommunication Union, Federal Communications Commission, National Telecommunications and Information Administration, and partners to ensure a permissive international environment for U.S. SSP satellites.

Federal Communications Commission

- ★ Develop application requirements and procedures for SSP-related frequency allocation and ground receiver antenna locations.
- ★ Manage the electromagnetic spectrum frequency application process and frequency use for nongovernment SSP satellite operators.

National Telecommunications and Information Administration

- ★ Develop application requirements and procedures for SSP-related frequency allocation and ground receiver antenna locations.
- ★ Manage the electromagnetic spectrum frequency application process and frequency use for government and military SSP satellite operators.

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3. Fostering the acceptance and development of representative institutions and free market economies throughout the world in a manner consistent with the Constitution, the national interest, and the values of the United States.

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