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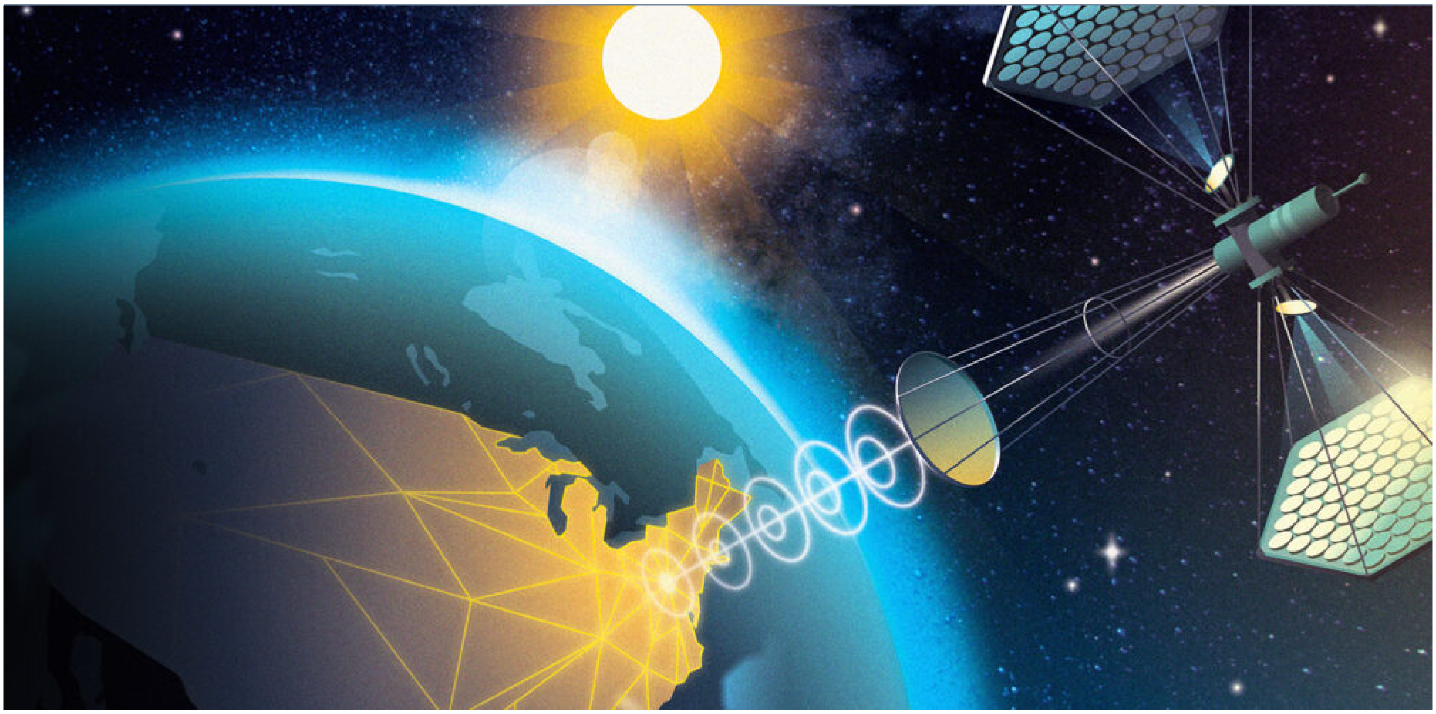

August 18, 2021

Space Solar Power: An Extraterrestrial Energy Resource For The U.S.

It is time to reconsider SSP as a valuable tool in the nation's decarbonization strategy

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EXECUTIVE SUMMARY

It's been 20 years since the first astronauts took up residence on the International Space Station (ISS) and marked the beginning of a continuous human presence in space. Yet rather than kickstarting a new era of space megaprojects, the ISS remains the largest space infrastructure program ever undertaken. Insofar as it catalyzed a robust American commercial space industry, it is considered a resounding success. Launch costs have plummeted and commercial operators have gained the experience they need to take over key operational activities from NASA such as resupplying cargo and crew to the space station. The increased efficiency and lower costs have allowed NASA to once again set its sights on more ambitious deep space efforts, particularly sustained crew operations on the lunar surface and a crewed mission to Mars.

At the same time, the reduced cost of space access has created unique commercial opportunities in low Earth orbit. Although we are still in the early days of in-space manufacturing, several American companies have made great strides in laying the technical foundation for an industrial cislunar economy. Moving heavy industry off-world would reduce greenhouse gas emissions and would accelerate our transition to a low carbon economy. This is an old dream — most famously articulated by the late Princeton physicist Gerard K. O'Neill[1] — but the technologies for realizing it are no longer science fiction.

What is often left unsaid in discussions about extraterrestrial industrialization and deep space settlement is how to supply the energy needed for large scale infrastructure projects. Nuclear energy has long been the power source of choice for deep space

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relatively low-cost, scalable, renewable, and always-on power source for on-and-off world applications. Although SSP is a space-based energy asset, it has the potential to rapidly accelerate decarbonization on Earth while also fulfilling space exploration priorities.

SSP is a decades-old idea that has only recently become economically viable due to the rapidly falling costs of space access and technological advancements such as higher efficiency electronics, low-cost mass-production of modular space systems like satellites, robotic in-space construction, and wireless power transmission. NASA, the Department of Energy, and several other research agencies have conducted in-depth studies and limited experiments on SSP, but the development of this energy resource was hindered by unfavorable economics. Things have changed and it is time to reconsider SSP as a valuable tool in the nation's decarbonization strategy.

This paper shows how the development of SSP can serve several national imperatives at once. In space, it can provide a renewable and cost-effective source of energy for moon bases and deep space missions. SSP can also provide a valuable source of energy — both electric and thermal — for industrial processes in cislunar space. This will facilitate the transition of heavy industry from Earth to space, which will mitigate carbon emissions in the medium-to-long term on Earth. Critically, SSP will have a massive impact on terrestrial greenhouse gas (GHG) emissions in the near term through wireless energy transfer from space to Earth. This is SSP's original "killer app," and multiple studies have shown that SSP can meet a substantial portion of Earth's energy needs. Unlike terrestrial solar power, SSP is always on. It can provide solar power rain or shine, day or night. It is also flexible and can be quickly redirected to ground stations in geographically distant locations to meet rapidly changing energy needs.

The dream for SSP is to have a source of clean baseload energy that's available regardless of weather, location, or time of day. The baseload is the minimum electrical energy demand on a grid, which has historically been provided by power stations that are able to generate large and relatively constant amounts of energy. But as more renewables penetrate the grid and create fluctuations in electric supply, the base load power stations of the future must be flexible enough to rapidly ramp up and down to meet the evolving supply and demand dynamics of the grid.

Much like the advent of GPS, a robust SSP capacity would have profound geopolitical implications. China is investing heavily in SSP and plans to have the first operating SSP plant in orbit by the end of the decade.[4] The Department of Defense (DOD) is also pursuing SSP research for military applications. Notably, the Air Force Research Laboratory recently created a $100 million program to advance key SSP technologies.[5] This paper concludes that the U.S. must allocate substantially more human and financial capital to SSP as part of its national security, domestic energy, and space exploration strategies.

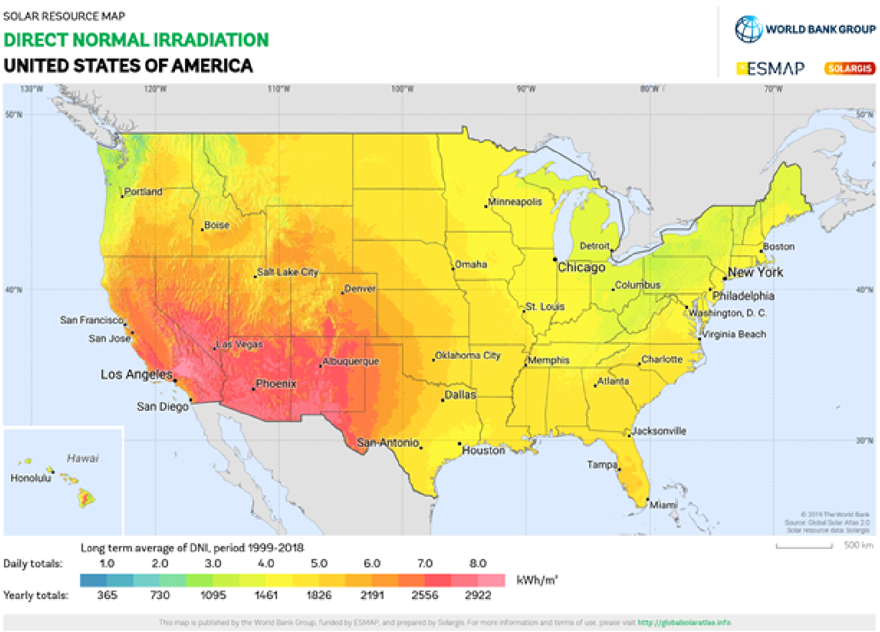
INTRO TO SPACE SOLAR POWER SYSTEMS

Space solar power (SSP) is the catch-all term for orbital systems that collect sunlight and convert that solar energy into microwaves or lasers and transmit that energy to receivers on Earth. On the ground, the electromagnetic energy is converted into electricity and delivered to the grid. A practical solar power satellite was first conceptualized in 1968 by Dr. Peter Glaser, an aerospace engineer at the American engineering firm Arthur D. Little.[6] He proposed a microwave transmission system to beam power from a solar satellite in geostationary orbit (GEO). This is a unique equatorial orbit 22,236 miles above the surface that allows a satellite to maintain a steady position relative to a point on the Earth.

Glaser's idea was ahead of its time. The first solar-powered satellite had only been launched a few years earlier and solar energy comprised a negligible part of power energy generation. A lot has changed in the past few decades. Today, solar power is widely used for terrestrial applications and is rapidly increasing its share of the power generation mix as a result of the plummeting cost and rising efficiency of solar cells.[7] Yet the expansion of terrestrial solar power is clouded by fundamental

AVAILABILITY OF SOLAR ENERGY: EARTH AND SPACE

The Earth is constantly bathed in enough solar radiation to meet humanity's energy needs several times over.[9] But only a small fraction of this sunlight can be economically harvested for power generation on the ground. The best conditions on Earth for collecting solar energy are found on a clear day at noon along the equator, where the power intensity of sunlight is approximately 1 kW/m^2.[10] But most systems have access to significantly less solar power. For example, the day-night cycle reduces the available sunlight by about half each day depending on the latitude. Likewise, seasonal variations can result in up to 60% loss of sunlight intensity depending on the latitude above or below the equator, with a greater latitude corresponding to wider seasonal variations. In fact, there can be up to a three-fold difference in available sunlight between the summer and winter months depending on the location of the solar asset. Weather variation is also a major factor: cloud cover can result in anywhere from a 20% to 90% reduction in solar energy depending on its thickness and persistence.[11]



Note that the annual total kWh peaks at around 3000 kWh/m^2 in the American southwest. This is equal to about 125 full 24-hour periods of peak irradiance (1 kW/m^2). A SSP platform would be exposed to a higher peak irradiance of 1.4 kW/m^2 24 hours a day, 365 days a year for a total annual irradiance of 12,264 kWh/m^2.

Terrestrial solar power is highly variable and limited to a power intensity of about 1 kW/m^2 under ideal conditions. In typical locations in the U.S., peak intensity is closer to 50-100W/m2 in the winter and 250 W/m2 in the summer, which makes solar poorly suited to supplying baseload power on Earth. Since space-based solar assets are not subject to atmospheric interference or seasonal variations and can always face the sun, they can always harvest solar energy at its peak intensity. In geostationary orbit, solar intensity is roughly 1.4 kW/m2.[12] This is roughly 40% more solar energy than reaches the surface of the Earth under ideal — yet transitory — conditions.

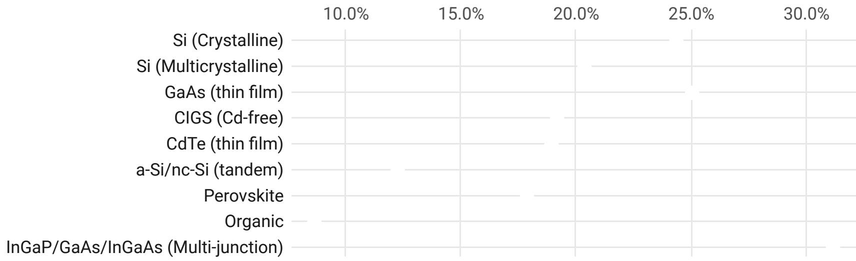
SSP ENERGY EFFICIENCY

No physical system is perfectly efficient, which means that not all of this solar energy can be captured by a SSP satellite. A space solar power system has three main components — the solar panels/collector, a transmission system, and a ground receiver — and each bleeds energy due to intractable hardware inefficiencies.

The cells used in solar panels on Earth are typically single-junction silicon cells, which have a maximum theoretical efficiency of around 33%,[13] although most commercial solar panels operate at closer to 20% efficiency.[14] Although significantly higher efficiencies have been achieved by using different materials, multi-junction cells, or solar concentrators,[15] these systems are substantially more expensive and many remain in very early stages of development. Currently, the world record for solar cell efficiency is just over 47%, which was achieved on a single experimental multi-junction cell using a solar concentrator.[16] This

Solar Module Efficiencies

Record efficiency of non-concentrating solar modules by type at 25C and 1000 W/m2.



Data from Table 4, Solar Cell Efficiency Tables (Ver. 57)

Source: Progress in Photovoltaics (2020) • Created with Datawrapper

When the solar energy is converted to electricity, it is delivered to a transmission system onboard the spacecraft to beam the energy to a receiver on Earth. These transmission systems come in two main types: microwave and optical.

Optical SSP systems use lasers operating in the near infrared part of the electromagnetic spectrum, which means they are not visible to the human eye. The main advantage of optical SSP transmitters are the short wavelengths of the laser, which allows for substantially smaller receivers on the ground.[17] (Beams of radiation spread out as they travel through space; longer wavelengths and larger distances create larger beam spots on the ground, which require larger receivers.) The primary disadvantages of lasers are they don't pass through clouds and are less efficient than microwave technologies. Typical solid-state lasers today have maximum efficiencies around 30% and photovoltaic receivers have efficiencies around 50%. When coupled with typical atmospheric absorption for infrared wavelengths, this means that the entire transmission system would have a total, end-to-end efficiency of around 10%.[18] Even assuming significant progress on the laser and photovoltaic receiver, future optical transmission systems are likely to max out at around 15% end-to-end efficiency.[19]

The limitations of optical systems have led many SSP researchers to focus on microwave transmission systems, which are not subject to atmospheric interference and can achieve significantly higher efficiencies. These transmitters would operate at wavelengths between 2 and 20 centimeters, which is thousands of times longer than the optical systems.[20] The longer wavelengths result in a corresponding increase in the size of the ground receiver on Earth. In most microwave SSP concepts, the ground receiver consists of an array of rectennas — a type of receiver that converts electromagnetic energy into direct current electricity — that work together to form the equivalent of a single large receiver. These arrays are massive: In most designs they cover areas on the order of several square kilometers. To put this in perspective, the largest radio telescope array in existence is the Square Kilometer Array (SKA) facility in South Africa, which will cover a single square kilometer when it is finished.[21] Although the size of a ground receiver for a microwave system is large, it is relatively modest compared to its power output. A 2,000 MW SSP system would require a ground receiver covering about 30 square kilometers. By comparison, the surface area of Lake Mead is about 600 square kilometers and feeds the Hoover Dam, which has a peak generating capacity of 2,000 MW.

The primary challenges associated with the ground portion of a SSP platform is the size of the receiver and the energy intensity at the point of reception. The actual receiver technology itself — rectennas in the case of microwave transmission and photovoltaics in the case of optical transmission — are relatively simple. In the case of a rectenna array, it would consist of millions of antennas each about 6 inches in size that could be fabricated in large sections in an automated factory and easily interconnected in the field.[22] A recent study found that the rectenna receivers could be deployed at a cost of about $10 per square meter assuming they are produced at sufficient scale (e.g., millions of receivers).[23]

larger the beam footprint will be on the ground. Likewise, shorter wavelength systems, such as high-frequency microwaves or near infrared optical systems can enable substantially smaller receivers on the ground. The design requirements of a SSP platform requires choosing either an optical *or* microwave transmission system rather than a combination of both. Thus, any SSP system must be developed in the context of a particular application to justify the tradeoffs between the efficiency and cost of both the transmitter and receiver.

A key policy issue associated with SSP platforms will be where to site the systems and how to ensure that they do not exceed safe energy intensities on the ground. Both factors suggest that any receiver will likely have to be placed in a sparsely populated area, such as the desert, open fields, or on a floating platform in the ocean.[25] In all of these cases, it would be necessary to build high-capacity transmission infrastructure to connect the receivers to the local grid.

The power intensity on the ground is related to the design of the space-based SSP components, but research shows that it is possible to build systems that will not pose a health hazard to humans or other life on the ground near the receivers. This would be accomplished by limiting the energy intensity of SSP to levels below 1,000 watts per square meter, which is comparable to full summer sunlight at the equator.[26]

AMERICAN SSP: PAST AND PRESENT

Despite SSP's promise, most research on the subject over the past half century has been conceptual with limited hardware demonstrations. In the decade after Glaser's groundbreaking paper, NASA and the Energy Research and Development Administration — the precursor to the Department of Energy — collaborated with industry on a handful of SSP studies. NASA's Jet Propulsion Laboratory and Raytheon, which invented microwave wireless power transmission, partnered for the first major experiment involving SSP in 1975. That test involved beaming more than a kilowatt of microwave energy from a Deep Space Network dish — typically used to communicate with NASA's exploration spacecraft — to a receiver built by Ratyehon located a mile away in the California desert. It remains the longest distance and most powerful demonstration of wireless power transmission to date.

In 1979, NASA and the Department of Energy published the first major study on space solar power that examined the costs and technical challenges associated with building a SSP platform. Known as the 1979 SPS Reference System, it consisted of a rectangular array of solar panels 20,000 meters long by 5,000 meters wide. The system would be capable of delivering up to 10 GW of energy — about 1% of today's installed generation capacity in the U.S.[27] — to a receiver array consisting of millions of small antennas — known as a rectenna — arranged in a circle 10 kilometers in diameter. The limits of 1970s technology meant the concept would have required assembling the platform in orbit using multiple space stations and the labor of hundreds of astronauts working side by side with thousands of robots. It would also require the development of fully reusable launch vehicles that would have been about five times larger than the space shuttle that was under development at the time.[28]

The 1979 SPS Reference System was as expensive as it was ambitious. The report estimated that the completed system would cost between $300 billion and $1 trillion (in current dollars) and take 20 years to build.[29] It would have been possible to begin using the system prior to its completion, but the report estimated that it would still require a $400-500 billion outlay (current dollars) to get to first power.[30] The federal response to the 1979 SPS Reference System study was overwhelmingly negative, and the congressional Office of Technology Assessment and National Research Council both issued scathing indictments of the concept.[31, 32] Not only were most of the technologies in a very low stage of development, but the exorbitant cost of the system was a non-starter. In 1980, the U.S. federal government eliminated funding for any further work on space solar power.[33]

Throughout the 1980s and early 1990s, there was little research on SSP conducted in the United States. Some American companies, including Boeing, sponsored small private research efforts, but most of the modest R&D work that happened

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required for SSP had matured enough to make the system economically viable, but NASA still rejected the proposal at the completion of the study. Possible reasons for NASA's continued rejection of SSP included the agency's focus on nuclear power for space systems and a general view among NASA's upper management that building space systems to generate commercial power is outside the agency's mandate.[36]

Although NASA leadership wasn't enthusiastic about the prospects of SSP, it did catch the attention of policymakers elsewhere in the federal government. Following the Fresh Look Study, both the House Subcommittee on Space and Aeronautics and the White House Office of Management and Budget recommended follow-on efforts.[37] As a result, Congress allocated additional funds to NASA's budget to conduct more research on SSP over the next three years with a focus on systems studies and limited technology demonstrations.

In 2000, about midway through NASA's follow-on SSP research program, NASA contracted with the National Research Council to produce an independent review of its SSP roadmap. The NRC concluded that the SSP roadmap was a "credible plan for making progress toward the goal of providing space solar power for commercially competitive electric power," but also acknowledged the significant economic and technical headwinds that would be faced by any SSP project. Still, the message from the report was clear: 20 years after NASA's 1979 SPS Reference System, space solar power had become an achievable and desirable goal.[38]

Internal resistance to SSP at NASA once again effectively halted research on the subject in 2003 and it wasn't until 2007 that the topic was revisited with federal dollars. This time, it was the Department of Defense carrying the SSP banner with its first-ever study on the concept for the National Security Space Office. The U.S. military was interested in SSP as a way to supply affordable, on-demand energy to remote DOD installations around the world. While the DOD study did not delve into technical details of a SSP system, it did underscore the valuable role for SSP in national security.[39]

Around this time, a handful of SSP startups were also formed in the United States. Arguably one of the most notable American SSP startups is Solaren, which was founded in 2001 and is still active today. Solaren's patented SSP system would use a solar concentrator to focus sunlight onto solar panels and beam the electrical energy back to Earth using a microwave transmission system. Although Solaren has yet to launch any hardware to space, it plans to launch a demonstrator unit within the next few years.[40] It also has the notable distinction of signing the first space solar power purchase agreement with PG&E in 2009.[41] The terms of the power purchase agreement required Solaren to begin providing service by 2016 and it is unclear if the purchasing agreement is still in effect.

Federal research on SSP has increased dramatically in the past five years driven by the rapidly falling costs of space access and geopolitical concerns. (See "Geopolitics of SSP" below.) The resurgence of SSP R&D has both civilian and defense dimensions. In 2012, NASA's Innovative Advanced Concepts (NIAC) program, which focuses on high risk, high reward space technologies, sponsored a research project on a new solar power satellite called ALPHA, which was the agency's first major SSP study in a decade.[42]

The ALPHA study was led by John Mankins, who was also a lead author on the agency's Fresh Look Study in the mid-1990s. ALPHA is arguably the most advanced space solar power reference concept produced to date and demonstrates how thinking around SSP systems has evolved over the past few decades. Whereas the 1979 space solar power Reference System was a monolithic structure that would require a lot of astronaut labor to assemble, ALPHA is a modular system designed to be assembled by autonomous robots.

The ALPHA platform would consist of thousands of relatively small reflectors that would be capable of moving independently of one another to maximize sunlight collection. The combined solar energy from these modules would be routed to a single large microwave transmitter at the aft end of the structure. Mankins proposed several different configurations for ALPHA, although most reference designs look similar to a bellflower whose petals are composed of interconnected solar panels. But

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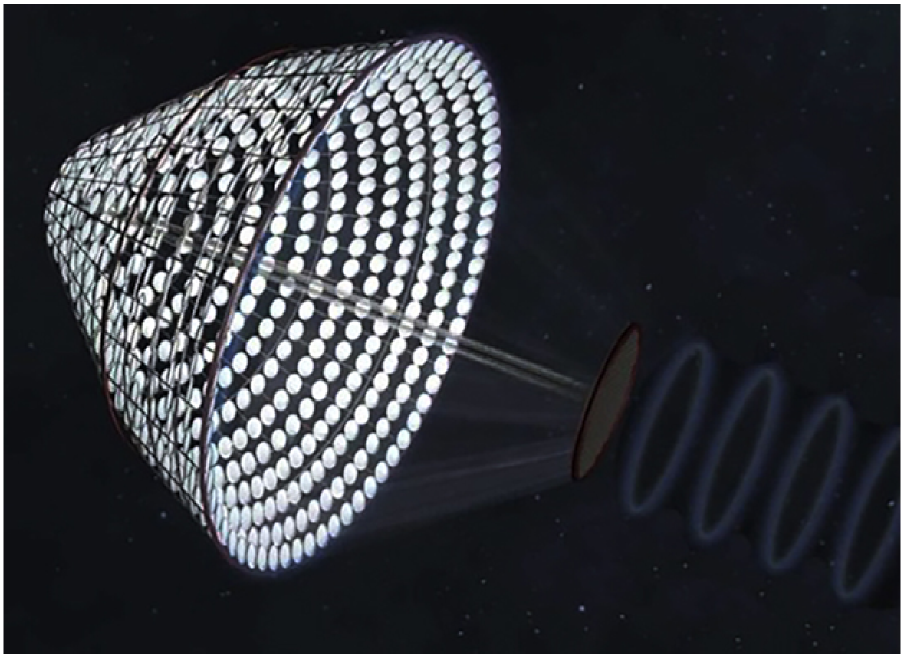

The SPS-ALPHA design developed by John C. Mankins as part of a 2012 NASA Innovative Advanced Concepts study.

Another notable development in civilian SSP was the creation of Caltech's Space Solar Power Project in 2015.[44] The 3-year program was funded with $17.5 million from Northrop Grumman and aims to develop ultralight SSP hardware.[45] In 2017, Caltech unveiled a series of prototypes of its SSP hardware and demonstrated that they could be used to collect sunlight and wireless transmit energy.[46] Although the scale of the demonstration was small, it represented an important advance from the realm of theory to functioning SSP hardware. Furthermore, the team demonstrated remarkable progress on reducing the weight of SSP modules, a critical design element that accounts for a substantial portion of the cost of an SSP system. Their prototypes were more than 10 times lighter than previous examples.[47] In 2021, Caltech announced a $100 million gift that it had received in 2013 from a private donor to work on SSP. The private funding will culminate in the launch of a 6-foot-by-6-foot space solar power platform that will demonstrate solar power generators and wireless transfer technology in 2023.[48]

There has also been notable progress on SSP in the defense sector driven by the Naval Research Laboratory. In 2019, NRL demonstrated a wireless power transmission system that beamed 400 watts of power between two receivers situated on each end of the David Taylor Model Basin, a large research wave pool in Maryland. Although this technology was developed to beam power from the surface to aerial drones, the researchers also highlighted its potential application to space solar power, which is another research area under active investigation at NRL.[49]

For the past few years, NRL engineers have been focused on developing hardware for a so-called "sandwich module" for SSP applications.[50] These modules consist of photovoltaics, DC to electromagnetic converters, and the transmission antennas stacked as layers in a "sandwich" configuration. This arrangement is desirable because it substantially reduces the complexity of distributing power from solar panels to a transmission system in a non-integrated system.[51]

After extensive testing on the ground, NRL launched a 12-inch sandwich module to orbit for further testing on the military's secretive X-37B spaceplane in May 2020.[52] The goal of the experiment, which is still ongoing, is to test how efficiently the sandwich module converts sunlight to microwave power in the vacuum of space. Preliminary results from the experiment published in early 2021, reveal an 8% efficiency for the module.[53] This is roughly half the efficiency of a low-end commercial solar panel on Earth and suggests the technology still requires significant development before it is ready for operational use. Although no energy will be transmitted from the space plane to Earth during the NRL experiments, they mark the first time that SSP hardware has been tested in orbit and marks a major milestone on the road to a full scale SSP system.

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Space solar power is primarily designed to meet terrestrial energy needs by providing a form of safe, scalable, renewable, and flexible baseload power. The United States must rapidly decarbonize its electricity generation if it is to meet its commitments to the Paris Climate Accord. SSP is an attractive option both for its ability to directly provide meaningful amounts of baseload power to geographically distant locations and for its role in facilitating extraterrestrial manufacturing, which can reduce domestic CO2 emissions by transitioning heavy industry from the surface into space.

FLEXIBLE BASELOAD POWER

The primary application for a SSP platform is to provide a source of flexible baseload power. Global electricity demand is predicted to grow by almost 50% by 2050.[54] To meet these growing energy requirements while simultaneously decarbonizing our energy systems is an immense challenge. Fortunately, the cost of conventional renewable energy resources like wind and solar have plummeted over the past two decades.[55] But these two resources are ill-equipped to provide baseload power due to the variability of the energy source.[56] Although this variability can be moderated by storing excess energy in large-scale battery packs, current battery chemistries are expensive and only able to store a few hours worth of energy.

There are a number of solutions available to alleviate the challenges posed by variable renewable energy resources. For example, advanced nuclear and geothermal power stations are both capable of providing carbon-free baseload power. But given the uncertainty around the international and domestic political support that is needed to support key technical breakthroughs to scale these technologies, it is prudent to pursue an "all-of-the-above" approach to energy decarbonization that includes SSP. Compared to SSP, the deployment of nuclear power stations is further complicated by negative public sentiment about the energy resource. Much like nuclear energy, SSP will require a sustained public engagement and education to overcome the perceived dangers of the technology. In the past, proposed SSP projects have created public concern about the possibility of these systems being weaponized or unintentionally causing harm by exposing humans and animals near the receiver to high doses of electromagnetic radiation. While numerous studies have shown that the SSP systems can minimize these risks and don't pose health threats, the success of an SSP program will critically depend on the clear communication of its safety features to the general public.[57]

Many of the enabling technologies for SSP, including in-space assembly robotics and wireless power transmission systems, still require substantial R&D before they can be deployed in an operational system.[58] Most of the core technological competencies for a SSP platform — in space solar arrays, wireless power transmission, and microwave receivers — have only been demonstrated on a small scale. Still, SSP is an attractive solution for flexible baseload power that avoids many of the challenges faced by these alternatives and also is uniquely equipped to increase the resiliency of the American grid.

AUGMENTING REGIONAL ELECTRICAL GRIDS

An SSP platform in a geostationary orbit has access to approximately one-third of the Earth's surface at any given time, which allows it to beam power to geographically distant locations. Current designs of SSP systems would allow the platform to switch its power beam from one receiver to another thousands of miles away in a matter of seconds. This is an incredible benefit from a grid management perspective, particularly in a country like the United States that lacks a fully integrated national grid. If there is a widespread power outage like the one that occurred in Texas in February 2021[59], a SSP system can rapidly reroute its power transmission to make up for the energy deficit. This is also a benefit during non-crisis situations since energy use reliably peaks at certain times of the day (morning/evening) and the SSP platform can be used to smooth the load spikes across time zones.

In this context, the cost and complexity of constructing an SSP system must be weighed against the cost and complexity of integrating the United States' grid. Connecting the balkanized U.S. power grid into a national grid is widely seen as the key to transitioning the country to 100% renewable energy.[60] The reason for this is due to the variable nature of key renewable energy resources such as wind and solar, which requires a careful balancing of supply and demand on a national scale. For example, there may not be enough local solar energy available to meet the spike in demand in the evening on the east coast

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Addressing this problem will require substantial investment in new transmission infrastructure that will consolidate America's regional electric grids into a unified national grid. The Biden administration's recent infrastructure proposal allocated $73 billion to expanding and modernizing the U.S. transmission system.[62] Some studies have found that the cost of modernizing and expanding the U.S. transmission and transformer infrastructure could cost upward of $2 trillion to reach 100% renewable energy penetration.[63] But even setting the costs of modernizing the U.S. electric grid aside, building thousands of miles of new transmission lines faces intractable policy challenges. The methods for allocating the costs of these projects can vary markedly from region to region or state to state, transmission planning zones are extremely fragmented, and new transmission lines are a perennial NIMBY hot button issue that is likely to draw strong opposition at the local level.[64]

A SSP platform is not necessarily an alternative to a unified grid, but it is a parallel pathway to further enhance the energy security of the United States. A SSP system could provide many of the same benefits of a unified grid at a reduced cost in addition to many unique capabilities that are not found in any terrestrial generation or transmission systems. Thus, an SSP platform can be a stopgap that bolsters grid resiliency and accelerates renewable penetration while new transmission infrastructure is built on the ground. Once the domestic grid is unified, it will benefit from the enhanced security and resiliency provided by the United States' SSP assets.

SPACE MANUFACTURING

The dream of moving heavy industries such as steel, cement, and chemicals manufacturing into space is nearly as old as the space age itself. It's a vision most famously articulated by the late physicist Gerard K. O'Neill, who envisioned a future with millions of humans living and working in orbital habitats. For now, this remains a distant goal. But the burgeoning commercial space sector is rapidly taking steps to turn it into a reality. Jeff Bezos, the founder of Amazon and the rocket company Blue Origin, has expressed his desire to turn O'Neill's vision into a reality on multiple occasions.[65] For Bezos, the ability to manufacture in space is a critical vector for decarbonization. Heavy industry contributes roughly one quarter of global greenhouse gas emissions each year and resist easy solutions for decarbonization due to high energy requirements of the processes and the long lifetime of the assets.[66] Moving these industries off world would significantly accelerate decarbonization efforts.

There are still a number of fundamental challenges that must be addressed before large scale in-space manufacturing becomes a reality. For example, basic manufacturing techniques such as cutting or welding metal have still not been demonstrated in microgravity. This is about to change in the near future during an uncrewed mission launched by Made In Space, which will demonstrate metal cutting in orbit for the first time.[67] While this will be a purely experimental mission, it is a critical first step toward scaling manufacturing practices beyond Earth.

But even if the critical in-space manufacturing tools were ready tomorrow, they would still lack a reliable and large source of energy to drive the processes. Heavy industry depends on substantial thermal and electrical energy inputs, but all spacecraft launched prioritized energy conservation. We simply haven't yet launched a substantial integrated energy resource (e.g., >1MW) to space.[68] (To give a sense of the scale of an SSP platform, SpaceX's Starlink constellation has the capacity to generate about 5 MW of electricity, but it is spread out over nearly 1,500 satellites.)[69] While an orbital nuclear reactor is one solution, this is still a developing technology and the first flight demonstrations of a space nuclear reactor aren't expected to occur until the middle of this decade.

In-space manufacturing presents something of a chicken-or-the-egg problem for space solar power. All SSP concepts proposed to date have assumed the ability to assemble the structure in space. But the costs of launching all the components from Earth are still high. Many of the raw materials needed for a SSP system can be sourced from asteroids or the lunar surface and if these could be used to manufacture the SSP components in orbit it would cause the cost of the system to plummet. In fact, in-space manufacturing may be key to making SSP a cost-competitive energy resource. But in-space manufacturing can't happen without access to a substantial energy resource. This suggests it may be necessary to absorb a

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DEEP SPACE EXPLORATION

In 2017, the Trump administration directed NASA to land humans on the Moon by 2024.[70] Known as the Artemis Program, the space agency aims to establish a permanent human presence on the lunar surface (i.e., a moon base) and use this outpost as a proving ground for the technologies that will eventually carry humans to Mars.[71] One of the main goals of Artemis is to advance the technologies required for in-situ resource utilization, which will allow astronauts to make productive use of lunar resources.[72] For example, a heat treatment process known as sintering can fuse lunar dust to create a concrete-like material for rocket landing pads, and frozen water can be broken down into its constituent elements — hydrogen and oxygen — which are the main ingredients of rocket fuel.[73]

The problem is that all these activities, including simply sustaining a human habitat, require far more energy than has ever been artificially generated in space. Moreover, the agency has shortlisted the Moon's south pole as a likely site for its first landing, which is a particularly inhospitable piece of lunar real estate.[74] To meet the energy needs of its planned lunar missions, NASA is developing small nuclear reactors capable of providing up to 10 kilowatts of power.[75] While these should be sufficient to meet the needs of a small lunar crew, they also come with important limitations. They must be sited sufficiently far from the lunar base to limit astronaut's exposure to nuclear radiation. Furthermore, these reactors are effectively immobile once they are operational. Because of the infrastructure required to transport the energy from the reactor to the load source, they cannot easily be moved to meet evolving exploration needs.

Conventional solar power on the lunar surface may also be an insufficient solution for future moonbases, especially around the lunar south pole. There are craters on the Moon's south pole that are permanently shadowed and others that receive near constant sunlight.[76] The challenge is that it may not be possible to simply put solar collectors in the permanently sunny craters and route this power to where resource extraction is happening in the shadows. These craters may be separated by kilometers of rugged terrain, which would require substantial investments in lunar surface infrastructure to route energy from the source to the end user. While there may be areas closer to the extractive operations that receive sunlight, this light will be intermittent. And like nuclear power on the surface, any large-scale solar installations are likely to be immobile.[77]

Space solar power is a strong alternative candidate for providing power for lunar surface operations. It is fundamentally safe for humans, it can be rerouted to different locations to meet changing mission requirements, and it can be scaled as necessary. While the size of both the solar collector and ground-based receiver is a limiting factor for lunar operations, the tenuous lunar atmosphere means that smaller systems that use laser light can be a viable option on the Moon.

ECONOMICS OF SSP

The economics of SSP has been one of the most pernicious issues for the technology since it was first conceptualized more than a half-century ago. There are two primary cost drivers of SSP: launch services and hardware.[78] There has been substantial progress in both areas over the past decade.

DECLINING LAUNCH COSTS

For most of the history of space exploration, the rockets used to place assets in orbit have been expendable, which substantially increased the cost of satellites and spacecraft. NASA's space shuttle was the first launch system to be partially reusable, but the costs of refurbishing the shuttle and its boosters after flight only resulted in marginal cost savings.[79]

In 2015, SpaceX launched and landed an orbital-class rocket booster for the first time and marked the advent of truly reusable rockets.[80] Since then, SpaceX has successfully landed boosters on more than 80 occasions, including the boosters used on a reusable heavy-class launch vehicle capable of delivering up to 50,000 kg to LEO and more than 6,000 kg to GEO. SpaceX has also demonstrated its ability to reuse its boosters several times and recently completed its ninth successful mission using the

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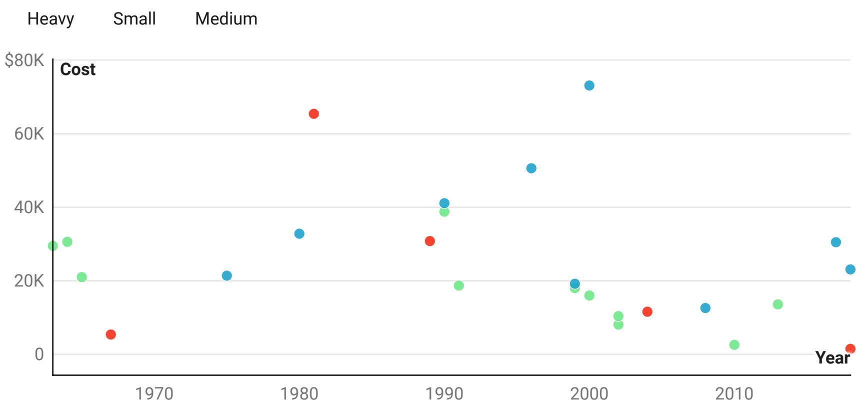
SpaceX's reusable rockets are a success story of NASA's commercial cargo program that supported their development. Between 1970 and 2000, the average cost to launch a kilogram to LEO was around $18,500/kg, but this could vary dramatically depending on the vehicle. The average cost of launch on the space shuttle, for example, was around $54,000/kg.[82] By contrast, the advertised cost delivering a payload to LEO with SpaceX's Falcon 9 rocket is just $2700/kg — a 20-fold improvement over the cost of the space shuttle. The economics improve even more in the case of SpaceX's heavy-class rockets, which cost 40 times less to deliver a kilogram of payload to LEO compared to the space shuttle.

American Launch Vehicle Costs (1963-Present)

Cost per kg to LEO by vehicle class: Small (<2,000 kg), Medium (2,000-20,000 kg), and Heavy (>20,000 kg)



Source: Center for Strategic and International Studies • Created with Datawrapper

The cost of space access will continue to decline with the arrival of still more powerful rockets. SpaceX's Starship is expected to deliver payloads to LEO — and perhaps even the lunar surface — at a cost below $100/kg. (SpaceX CEO Elon Musk has cited a possible price point as low as $10/kg to LEO on multiple occasions, but this aspirational goal depends on several variables such as the payload destination and annual launch cadence.)[83] And while SpaceX has been a clear leader in the development of reusable rockets, it is not the only company working on the technology. Blue Origin, the rocket company founded by Jeff Bezos, is also developing its heavy-class New Glenn rocket that will be capable of delivering 45,000 kg to LEO and around 14,000 kg to GEO.[84]

A competitive market that features multiple launch services providers with reusable rockets will further reduce the costs of space access. Additionally, the development of new technologies such as on-orbit refueling and "space tugs," a type of spacecraft used to boost cargo into higher orbits once it's in space, create the opportunity for lowering costs further by dramatically increasing the amount of payload that can be delivered to geostationary orbit. This is a critical development for SSP, which will require launching thousands of tons of hardware to GEO for a commercially viable platform.

DECLINING SPACE HARDWARE COSTS

Low launch costs are imperative for a large-scale SSP system, but arguably the primary cost driver is the cost of the SSP hardware itself. In the past decade, there has been a substantial decrease in the cost of space hardware as a result of advances in materials science and new approaches to manufacturing spacecraft.

In the context of SSP, one of the biggest advances in recent years has been the declining cost of solar panels. Between 1975 and 2020, the cost of photovoltaic modules has decreased from more than $100/w to less than $1/w.[85] Of course, the cost of PV modules varies substantially depending on their design, the materials used, and the scale of production, but the overall trend

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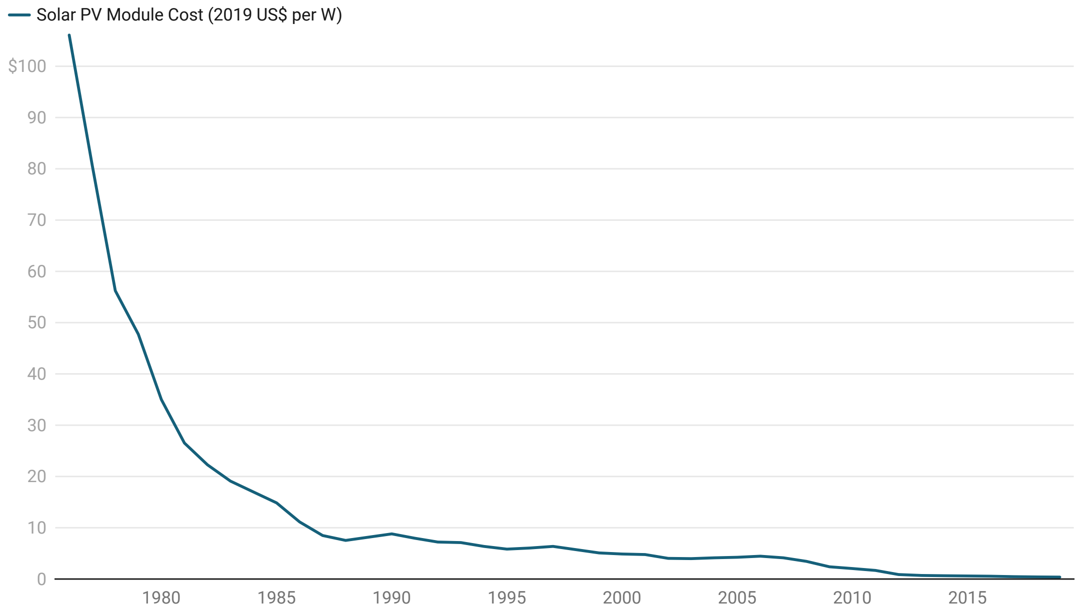
Solar PV Module Prices (1976-2019)

Global average price of solar photovoltaic modules



Source: LeFond et al. (2017) & IRENA Database • Created with Datawrapper

Whereas most solar systems on Earth are likely to use relatively low-efficiency, single-junction silicon cells, the photovoltaic systems used for spacecraft tend toward high efficiency photovoltaics such multi-junction or gallium-arsenide cells.[86] Historically, the high-performance solar cells used in space applications were far too expensive to produce for large-scale terrestrial power applications or SSP. But the cost of these cells is also falling rapidly driven by new manufacturing techniques developed in the U.S. National Labs.[87] While a full discussion of the merits of various PV technologies in the context of SSP is beyond the scope of this paper, the bottom line is that a large-scale SSP platform has become substantially more cost effective due to the development of low-cost, lightweight, and high-efficiency solar cells over the past few years.

A SSP platform capable of providing baseload commercial power will necessarily be incredibly large. This means it will require inexpensive, lightweight materials that can be mass manufactured for its core structure. While nothing on the scale of an SSP platform has ever been built in space, the International Space Station demonstrated fundamental concepts such as the robotic assembly of modular components that will be required to build an SSP platform.[88] But despite the ISS being a sort of proving ground for large-scale space infrastructure, it came at an incredible cost. By the time the final core modules were added to the ISS in 2008, the cost of building the space station clocked in at around $100 billion.[89] While this is not a perfect comparison (e.g., the ISS must support crew, which adds substantial costs), it's clear that if SSP is going to be commercially viable on Earth, the costs of building large-scale infrastructure in space must be dramatically reduced.

Since the beginning of the space age, the approach to building spacecraft has been to treat them as unique objects. This required building specialized hardware and creating spacecraft-specific building processes, which substantially increased the cost of a spacecraft. But the past decade has seen the rise of large-scale manufacturing for space hardware, which opens the door for low-cost, large-scale space infrastructure.[90] This was first driven by the development of cubesats in the 1990s, which use standardized form factors and hardware to enable the rapid and inexpensive development of on-orbit testbeds. Today, cubesats are used for everything from Earth observation to Mars missions at a fraction of the cost of entirely bespoke satellites in the past.

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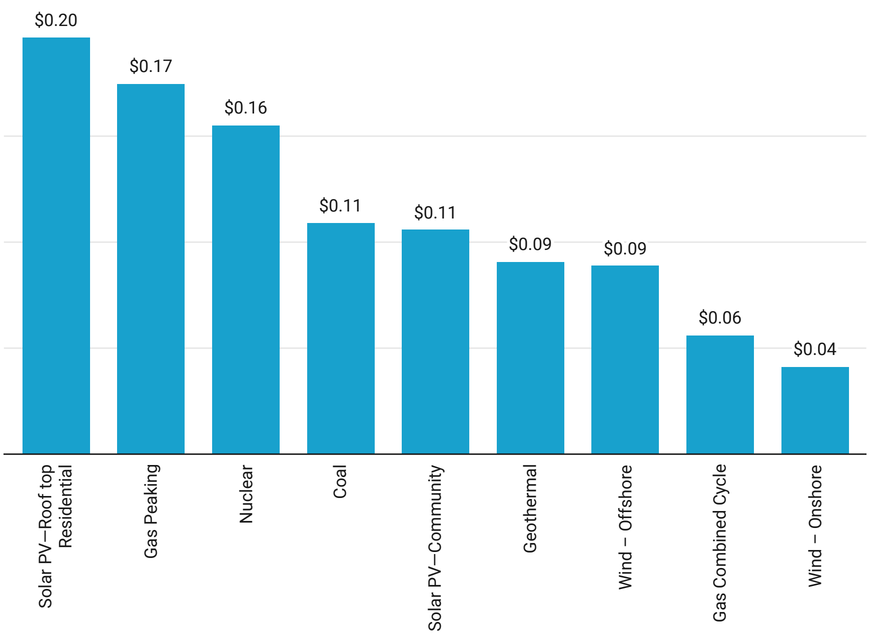
been approved for 12,000 satellites and is currently petitioning the FCC to permit up to 30,000 additional satellites for the network.[91] Since the company first started launching operational Starlink satellites in 2019, it has single handedly doubled the number of operational satellites in orbit. By the time it completes its 12,000 satellite constellation, SpaceX will have increased the total number of operational satellites in orbit by a factor of six.[92]

Achieving the satellite production cadence that is required to create a mega constellation like Starlink would have been impossible with conventional satellite manufacturing techniques. By standardizing the spacecraft hardware, however, SpaceX was able to mass manufacture its internet satellites and now produces more than 30 tons of operational satellites with a total of 500-600 kW of power generation capacity at its facilities every month.[93] This is roughly the cadence that would be required to build a commercial SSP system and is a critical proof of concept that it is possible to build substantial amounts of flight-ready space hardware through the use of modular, standardized components.

These are key foundational breakthroughs required to create a large-scale SSP platform, especially one based on a modular design. We believe that the plummeting costs of space access and hardware make it possible to build a 2 GW SSP platform that can provide flexible baseload commercial power to the grid for under 10 cents/kwh, which would make it competitive with terrestrial renewable energy resources.

Average Levelized Cost of Energy by Technology in US 2019



As of 2019 in USD

Source: Lazard • Created with Datawrapper

GEOPOLITICS OF SSP

The geopolitics of space solar power are best understood along two dimensions: diplomacy and national security.

SSP is valuable as a diplomatic tool both during its construction and operation. The assembly of such a massive piece of space infrastructure will almost certainly involve international participation due to the substantial costs of construction. But even if

In each instance, there are important historical precedents to consider. The International Space Station began its life as a national project of the United States called Space Station Freedom.[94] But as costs ballooned and policymakers began to sour on the project, NASA opened the station to international partners. The lessons learned from the internationalization of the space station, such as bringing partners into the conversation early, the clear delegation of responsibilities, and equitable cost-sharing agreements are directly relevant to the construction of a space solar power platform. Similarly, there is also a precedent for establishing operational norms for space. The 1967 UN Outer Space Treaty remains the guiding document for all spacefaring nations and also establishes a basic framework for the operation of SSP assets (e.g., their beamed energy cannot be used as a weapon). Fortunately, the community of researchers working on SSP are already well acclimated to international cooperation and consensus building from decades of workshops and conferences dedicated to the subject.

SSP can also play a vital role in national security.[95] Just in the past year there have been multiple high-profile failures of the U.S. electricity grid from extreme weather events, such as the unprecedented wildfire season in California and the cold snap in Texas. The vulnerability of our energy supplies to cyberattacks was also exposed during the recent breach of the Colonial Pipeline. Cybersecurity experts expect that state-sponsored attacks of critical infrastructure, particularly energy infrastructure, will become more frequent in the future and have raised concerns that the U.S. grid is unprepared to adequately manage this threat. SSP can bolster the resiliency of the U.S. electric grid by rapidly delivering clean energy to affected regions of the U.S. in the immediate aftermath of a natural or man-made disaster.

SSP can further play a role in national security by supplying cheap and readily available clean energy to remote U.S. army facilities and U.S. forward operating bases.[96] It would prove to be especially valuable in the latter case given the high cost of supplying these bases with electricity. Typically, they rely on fossil fuel-powered generators, but delivering these fuels to the base can be dangerous and incredibly expensive. During the early days of the Iraq war in the mid-2000s, for example, the cost of generator fuel for these bases ranged from $15 to well over $100 per gallon.[97] A 2009 study from Deloitte underscored the risk that fuel transportation poses to American soldiers, concluding that "During the modern age of warfare, the use of fossil fuels to power these vehicles has increased exponentially and this dependence has itself created casualty risk."[98] If SSP is used to reduce the U.S. military's reliance on fossil fuels to power their forward operating bases, it could save both money and lives.

A key limiting factor in the use of SSP for remote military installations is the size of the ground receiver required for SSP. According to researchers at the U.S. Naval Research Laboratory, however, it should be possible to build modest receivers that are able to generate power on the order of 10 kilowatts to 10 megawatts, which is sufficient to meet the needs of most forward operating bases. In the baseline model proposed by the researchers, such a receiver would occupy 0.8 square kilometers or less. This would also require a substantially smaller space-based collector and transmission system compared to the massive platforms required to deliver baseload energy to the grid.[99]

Finally, SSP can also be a powerful diplomatic tool that can be used to help developing nations decarbonize their electric grids through power purchasing agreements. Climate change is ultimately a global problem and extraterrestrial energy assets are particularly well-suited to address the challenges associated with decarbonizing the world's electricity.

The economic, political, and security benefits of SSP are well-understood by both allies and adversaries of the United States. In particular, Japan and China have made the development of SSP a central priority of their space exploration programs. Japan has been actively researching and developing experimental SSP hardware since the early 2000s.[100] In early 2019, China announced its intention to build a megawatt-scale SSP platform by 2030 and create a gigawatt-scale SSP station by 2050.[101] India and the European Union are also pursuing their own SSP projects.[102, 103] In late 2020, the UK conducted its first major assessment of space solar power and identified it as an important option to achieve its national carbon net-zero goals by mid-century.[104] This makes the United States the only major space faring nation whose national space agency does not have a serious plan to develop a SSP platform.

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The United States' reluctance to pursue SSP can be attributed to a number of causes. In the 1970s and 80s, the exorbitant projected costs of an SSP station guaranteed that the project would not be pursued by NASA, the DOE, or the DOD. At the same time, the agency's emphasis on developing nuclear space technologies — a trend that continues to this day — undermined enthusiasm for other ambitious energy projects like SSP. Finally, the fact that SSP is a space project meant to provide commercial levels of electrical power on Earth meant that it wasn't obvious whether it fell within the purview of NASA or the DOE, and so both agencies were reluctant to allocate a substantial portion of their budget for its development.

Today, the low cost of natural gas and renewables like wind and solar makes it seem challenging to justify a space energy project of this scale. But SSP offers several unique benefits as an energy resource, including its resiliency, its ability to provide flexible baseload power to geographically distant locations, its capacity to accelerate decarbonization directly by providing clean energy and indirectly by expediting the transition to off-world heavy industry, and its strategic benefits as a tool for diplomacy and national security.

Given SSP's benefits and the interest in the technology from most other space agencies, it's puzzling that policymakers in the United States have not prioritized SSP R&D. The development of key technologies such as reusable rockets and thin film solar panels has finally made SSP economically and technically viable. But there is still a lot of fundamental research on SSP that needs to be done and it is in the United States' national interest to begin this research program as soon as possible.

So far, the only glimmer of hope for an American SSP program has come from the DOD's efforts. In 2019, the Air Force Research Lab awarded a $100 million contract to Northrop Grumman as part of the new Space Solar Power Incremental Demonstrations and Research (SSPIDR) Project, which aims to develop hardware for in-orbit SSP experiments based on the design developed at Caltech.[105] This is by far the United States' largest federal expenditure on SSP R&D, but it is only a fraction of what will be required to build a large-scale SSP station and the specific technologies included in the SSPIDR program will not result in a system that could ever provide commercial power to civilians.

SSP is a key tool for ensuring the prosperity and security of the United States in the latter half of the 21st century. It is imperative that NASA and the DOE prioritize the development of SSP. We believe the federal government should earmark approximately $1 billion for SSP research over the next five years with a special emphasis on advancing emerging technologies and in-space hardware demonstrations.

Congress must take the first step in establishing a civilian SSP platform by directing NASA and the DOE to collaborate on a public-private initiative similar to NASA's commercial crew program or its more recent commercial lunar payload services program. The directive must clearly delineate responsibilities between the agencies in order to avoid leadership paralysis that has stymied domestic SSP research in the past. Furthermore, a public-private program must be structured so that there is competition among multiple private companies, which must hit key milestones in order to continue receiving contracts. These contracts should be awarded with a fixed-price structure to avoid the massive cost overruns and delays that are typical of cost-plus contracts in the aerospace and defense sector. This is also an approach likely to find support among new launch providers and spacecraft manufacturers that have demonstrated the innovation that occurs when operating within the relative constraints of fixed price contracts. In fact, the main trade group for the aerospace sector has advocated for the increased use of fixed-price contracts in the past.[106]

Alternatively, it may be more efficient to establish a focused research organization (FRO) dedicated to SSP technologies to avoid delays associated with collaboration between two federal agencies on multi-year—and perhaps multi-decade—projects. FROs are independent entities that exist outside of national laboratories and universities. They are effectively a startup for basic research and deep technological development that requires large-scale engineering collaboration on technologies that may not yet have a market or are not readily monetizable.[107] Recently, the U.S. Congress created five FRO-like centers in the DOE's national labs as part of the National Quantum Initiative Act, which can serve as a framework for the creation of similar FROs dedicated to space solar power.[108]

civilian SSP demonstration in low-Earth orbit within three years of the program's start with less than $250 million in funding. The first phase of this program would involve conducting a series of ground tests with prototype systems over the course of about 18 months. Based on the results of this program, a system could be selected for an in-space demonstration capable of generating up to 300kw of power in low-Earth orbit.

After a successful LEO demonstration mission, the next step would be to build a larger SSP system in mid-Earth orbit capable of producing commercial amounts of power (e.g., 1-10 MW). While this orbital altitude is not sufficient for maintaining the SSP system over a fixed spot on the Earth, it would stay on a fixed path so that it always passed over the same spots on the Earth. While the power from this MEO demonstrator would not be competitive with terrestrial electricity prices — we expect a cost of about $1/kwh — it would be a critical step toward proving the system's ability to provide commercial power. We expect that the MEO demonstrator could be built and launched for approximately $1 billion.

The success of the MEO demonstrator would lay the foundation for an SSP system in geostationary orbit that would be large enough to provide meaningful amounts of baseload power. We expect the initial version of this SSP system to be capable of delivering around 2 GW of solar energy to the surface. We expect that a 2 GW SSP system in geostationary orbit could be built for about $10 billion. Here we start to see the cost savings of mass manufacturing modular SSP components. This system would be capable of delivering more than 200 times more power than the MEO demonstrator for only 10 times the cost.

We believe that a public-private SSP program jointly led by NASA and the DOE could result in a commercially viable SSP platform in geostationary orbit by the end of the decade. In addition to providing a critical pathway for SSP, it also has the potential to lead to substantial advancements in solar power and wireless power transmission technologies that would be useful on Earth. If policymakers do not take action on advancing domestic SSP capabilities soon, the United States will find itself losing its leadership position in space and increasingly vulnerable to natural and human-made disasters on the ground.

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