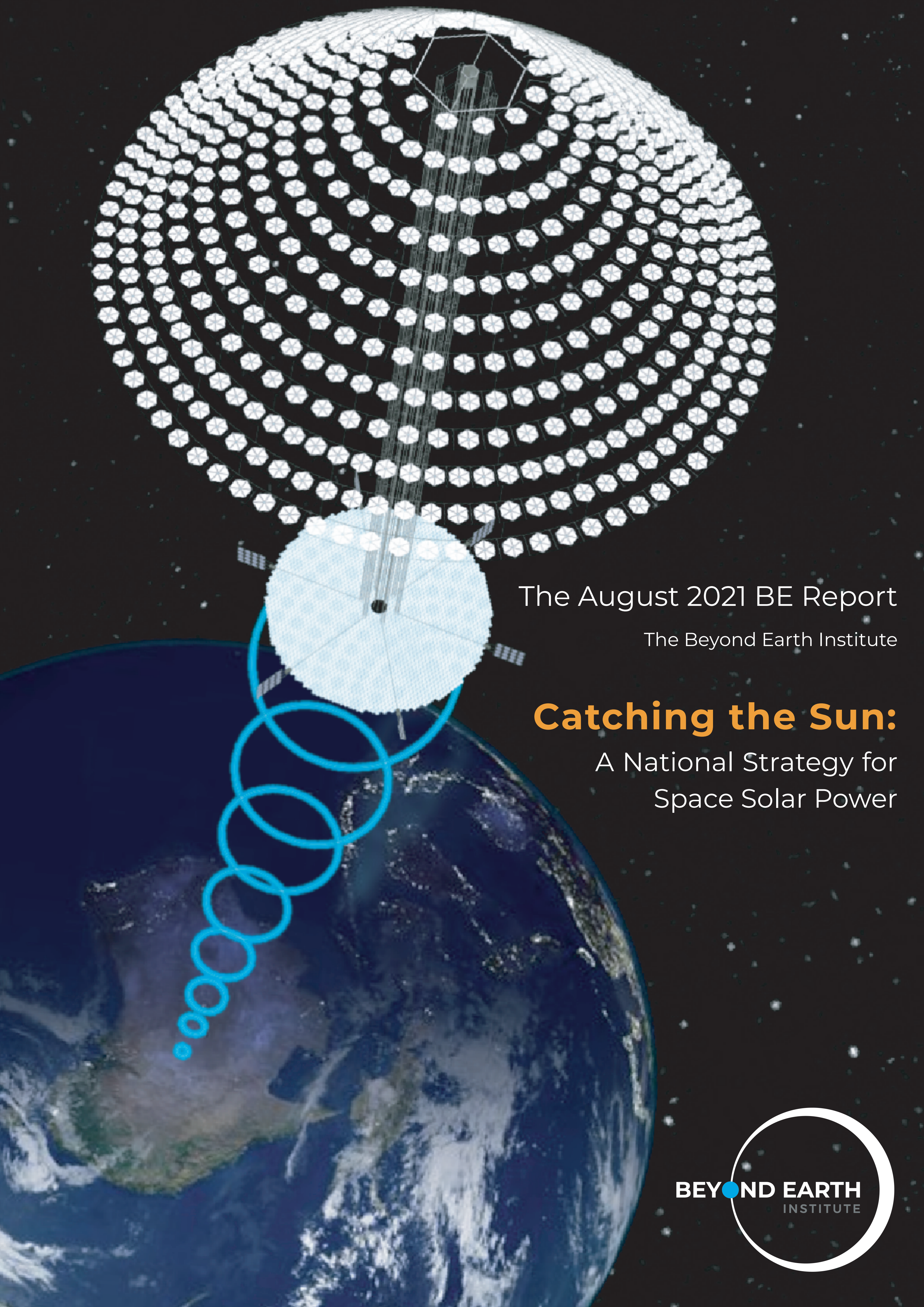


The August 2021 BE Report

The Beyond Earth Institute

Catching the Sun:

A National Strategy for Space Solar Power

BEYOND EARTH INSTITUTE

Issued by

Beyond Earth Institute

Executive Summary

Space Solar Power can fulfill the promise of clean, safe, renewable, affordable energy reliably delivered where and when it is needed. Space Solar Power can power the world, and power worlds beyond, while moving our civilization beyond the fossil fuel age. Having developed all the underlying technologies, America can and should take the lead in creating this better tomorrow.

Space Solar Power is a broad term for power generation and distribution systems that collects the Sun's energy in space and delivers it to nearly any point on Earth where the energy is required. Space Solar Power systems are designed to be safe and will not harm birds or aircraft in the sky, nor will they harm humans, animals, vehicles or structures on the ground. By continuously harvesting sunlight in space, outside of the day/night cycle and above the obscuring atmosphere and weather, Space Solar Power yields up to 40 times greater sunlight access than traditional ground solar systems.

Space Solar Power has been theoretically possible for years, but economically grounded. New American technology is driving two Space Solar Power-enabling trends: significantly lower space launch costs and lower space hardware costs due to advanced manufacturing. Our geopolitical competitors see the possibilities and are eagerly pursuing dominance of this promising technology.

America needs a strong national commitment to Space Solar Power and a directed Space Solar Power research and development program. We must leverage the full array of governmental and private resources to produce a full-scale demonstration of Space Solar Power. Such a demonstration should provide a pathway for an economically sustainable approach, including involvement of international and private sector partners.

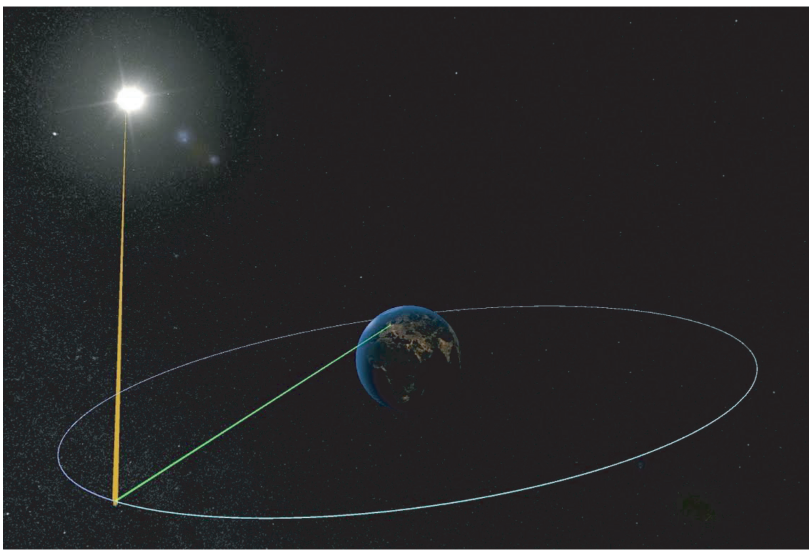
Space Solar Power is a critical enabler for space exploration and development, leading to communities of people living and working beyond Earth. It is an important step in securing the future of human civilization and our achievements as a nation.

What is SSP?

Space Solar Power (SSP) is a broad term for a power generation and distribution system that collects the sun's energy in space, converts sunlight into transmissible wavelengths, and uses wireless power transmission technologies to safely and efficiently convey the energy to remotely-located receiving antennas, which can be placed almost anywhere on Earth where the energy is needed.

In the 1960s and 1970s, an era known for people first rocketing their way into orbit, solar photovoltaic (PV) arrays were first being applied in space, and wireless power was demonstrated. With a spark of inspiration, Dr. Peter Glaser of Arthur D. Little invented the solar power satellite. Dr. Gerard K. O'Neill, physicist of Princeton University, subsequently popularized the concept of SSP as part of his idea for human settlements in space.

Space is an ideal location to harvest sunlight for multiple reasons. The Earth's atmosphere absorbs radiation. Outside of the atmosphere, sunlight has a greater energy concentration. According to NASA, "roughly 340 watts per square meter of energy from the Sun reach Earth. About one-third of that energy is reflected back into space." [1] In space, orbits can be selected to avoid the Earth's shadow and the resulting day-night cycle we all experience, guaranteeing nearly full-time sunlight. "Atmospheric conditions can reduce direct beam radiation by 10% on clear, dry days and by 100% during thick, cloudy days." [2] Finally, weather can block the sun for days or weeks at a time (i.e., clouds, fog, rain, snow, etc.) meaning the available sunlight in space can be 10-40 times greater than that available on Earth.



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How does it work?

SSP includes systems to collect, convert, transmit, receive, and distribute energy from the Sun. Solar Power Satellites are designed to collect the Sun's energy with large solar arrays. The amount of energy that can be collected is determined by the size of the solar panels, their location in Earth orbit, and the efficiency of the solar cells. The satellites also contain the equipment necessary to convert the sunlight into electricity and transmit it wirelessly to receiving antennas on Earth.

The electricity needs to be delivered from the satellite in space to the ground without using wires. Wireless Power Transmission (WPT) enables the transfer of energy from one location to another by means of electromagnetic (EM) waves – and hence, without wires or cables.

This is the perfect solution for transmitting the energy from space or in circumstances where power lines won't work, such as over very rough terrain or to moving vehicles or systems. The effectiveness of the end-to-end energy transmission depends on many factors: the equipment used, the power transmitted, the distance between the Transmitting Antenna in space and the Receiving Antenna on the ground, the size of each antenna, and the wavelength of the EM waves used between them. The Receiving Antenna captures the arriving EM waves and converts them into electricity. That electricity is then processed and delivered to the local power grid.

Why is Now the Time for SSP?

The physics for SSP is well understood, and the required technologies have long been available. So, why hasn't Space Solar Power been adopted yet? Why is now different?

A great many paper studies have been written since the 1970s, and periodic technology development efforts undertaken. However, affordable systems did not emerge as quickly as many hoped. The central hurdles to SSP demonstration and use in the past have been economic. The costs of launch and of the infrastructure required for assembly, the costs of the system hardware itself and the poor efficiencies of key devices (such as wireless power transmission) overwhelmed any prospect for delivering cost-competitive electricity to Earth. However, important advances since the turn of the 21st Century have greatly improved the potential economics for SSP. Specifically, low-cost launch, mass-production of modular space systems, advanced artificial intelligence, robotics for assembly, as well as other areas.

The United States enacted a series of laws that opened up space for commercial ventures and users. As a result, there have been tremendous advances in launch capabilities initially led by SpaceX, but industry-wide in the years since, by commercial firms. Commercial innovation driving down launch costs include reusable first stage rocket boosters, dramatically improved manufacturing efficiency, and improved operational efficiencies. The cost of launch has seen a 90% reduction in only the past 10 years as the SpaceX Falcon Heavy can now deliver a payload to Low Earth Orbit for $1,500 /kg. [3] As these new systems mature and new launch systems, such as SpaceX Starship, come on line, the cost of launch will continue to significantly decline.

While this revolution in launch cost has been happening, computing power continues to follow Moore's Law enabling increased efficiency and new capabilities while reducing the cost. We now have systems that fit into a shoebox that have all the capabilities it used to take a satellite the size of SUV to perform. Moreover, constellations of such modular satellites are now being manufactured in the thousands of units, and hundreds of tons. The Aerospace Corporation stated that "traditional cost models—based on larger civil and military space systems—tended to drastically overestimate the development costs of modern, smaller satellites" [4] and as hardware continues to get smaller, those cost gaps increase. As a result of technology advances and modular architectures, the cost of the hardware used in these small satellite constellations is roughly 99% cheaper than the cost per kilogram of conventional spacecraft – while also being up to 90% smaller in size for the equivalent functionality. [5]

These two factors – lower launch cost and lower hardware cost – enable SSP. For example, companies like SpaceX have been putting up mega-constellations – constellations of up to tens of thousands of individual satellites. SpaceX has launched 1,740 satellites to date in their StarLink constellation, [6] each with a mass of about 250 kg and deploying PV panels that generate roughly 5 kW of solar power.

That's a total of more than 8,700 kW of solar power – some 40-times the average power on the soon to be fully upgraded International Space Station (ISS). [7] The overall cost-effectiveness for solar power in space has improved by a factor of more than 100-to-one. More improvements are needed, as in-space cost estimates of space solar are still higher than terrestrial solar. Directed research and development, plus further reductions in launch costs and hardware costs, drive expectations that in-space solar costs will continue to fall.

Why is SSP the right goal for America today?

SSP is the right goal for America today because it can enable America to become the global leader in clean, safe, renewable, reliable, affordable, distributable, anywhere, anytime energy. SSP can power the world, and power worlds beyond, while moving the world off fossil fuels forever. By taking a leadership role on SSP today, we can create a better tomorrow.

Climate

The global understanding of climate change and concerns about its impacts have swelled, creating intense demand for new energy solutions for Earth. SSP is carbon-neutral and eliminates criterion pollutants in energy generation. SSP is clean, renewable, capable, and the only energy source that provides baseload power in a safe, reliable, and wasteless system.

Reliance on other renewables can sometimes create new environmental concerns. Some estimates show that terrestrial solar power may occupy up to 5% of total land area if it is to become a primary energy source, [8] while SSP has significantly reduced land-use requirements for clean energy generation.

The receiving antennas on Earth do not require dedicated land, so the land can still be used safely for agriculture, commercial, office, residential, and industrial uses while collecting the power from space.

Baseload Energy

SSP not only holds the promise of energy independence for America, but at scale it can also provide baseload power to all the people of the world. Baseload power is the minimum amount of electrical power needed on the grid at any time. While Earth-based solar power has become an important part of our energy mix, sunlight availability is 10 to 40 times greater in space with more energy available per square meter outside of Earth's atmosphere. Solar power satellites are not impacted by weather. With the recent advancements and continuing progress, a focused effort could achieve a full-scale demonstration within a decade.

Remote Energy

SSP enables energy distribution to remote locations. Many energy-intensive operations need to take place away from the existing grid. SSP enables them without batteries, generators, and massive amounts of fuel. SSP enables energy to offshore desalination plants, to offshore carbon capture plants, and to other locations where off-grid energy is needed.

SSP is currently under development by the U.S. Department of Defense to address their remote energy needs. There are two separate R&D projects, one at the Naval Research Laboratory and one at the Air Force Research Laboratory. These projects may well lead to deployable SSP to meet the needs of the military, but those needs do not translate into economically viable commercial-scale SSP. There are many reasons why these programs, even with significant funding increases, would not be sufficient to provide the leadership under discussion. The scale, the economics, and the technical requirements would all be significantly different when meeting these different needs.

Redundant Energy Source

SSP enables instantaneous backup power generation for locations who choose other energy sources as their primary systems. Currently, when relying on wind, solar, or other naturally variable sources, backup power generation must be available. In practice, this means that coal or oil systems are kept operating with the ability to take over generation needs. With terrestrial systems, this change can happen quite spontaneously, so the backup system needs to be available all the time, and the operators need to remain in a constant state of readiness. SSP can provide backup power, removing coal and oil backup systems from the loop.

Disaster Response

SSP could provide power availability for areas whose power generating capacity was impacted by a natural disaster. Disasters destroy infrastructure and it takes time to rebuild, reconnect, and return to the pre-disaster state. Time between the system being destroyed and being reconnected can be counted in lives lost, and property irreparably damaged. Receiving antennas are easily deployable, so SSP could fill in for a power station that has been taken offline, enabling power to be restored to hospitals, homes, and businesses more quickly, saving lives and property.

Space

International efforts to develop the resources of the Moon have also grown and would require large-scale affordable energy. SSP can provide energy in space – at the Moon, at asteroids, in Earth orbit – supporting our science missions, and enabling more ambitious projects.

Energy is a constant need and SSP can provide for the power needs of missions. It enables certain mission types, mission lengths, mission safety, and mission reliability. The more energy that is available, the more life support, the more redundant systems, the more habitable volume, the more science, the more mining, the more commerce, the more agriculture, and the more human activity can take place. SSP holds the promise of providing continuously renewable energy to any place in the inner solar system, on a planet or off one.

International Activities

Other countries are engaging on space solar power as well. China is pursuing any new technology that holds significant promise, and SSP is no exception. Russia has used in-space solar panels for years. India, Japan, UAE, the U.K., and the European Union, are all interested in making this technology work for their needs.

China in particular, has made significant progress toward space solar power during the past decade, developing a dedicated facility for the R&D and establishing in Spring 2021 a national committee to coordinate SSP research. China has announced plans to conduct a major SSP demonstration by the mid- 2030s. [9]

In Japan, Mitsubishi conducted major demonstrations of wireless power transmission in 2015.

Continuing Japanese R&D on key SSP technologies includes deployable structures, high-efficiency solid state devices and other topics.

The United Kingdom (UK) during 2020-2021 conducted the first-ever assessment of space solar power for the UK under the joint-auspices of the Ministry of Business, Energy and Industrial Strategy (BEIS) and the UK Space Agency. [10] An announcement is expected by the Fall of 2021 of a significant commitment to SSP at the national level.

South Korea, India and Australia have seen interest and studies undertaken by universities, for-profit firms and government Agencies. Other countries are also taking some of these steps and showing interest.

It is important to note that even if the U.S. were to adopt an aggressive program immediately to develop SSP capability, such international efforts are unlikely to wane. Our work will run parallel to other efforts already underway. Only through the strongest statement and commitment at the national level, and a directed research, development, and demonstration effort can America seek to claim leadership in SSP. While that may be challenging, for the U.S. to allow other nations, particularly adversarial nations, to move ahead on SSP while we limit our investment will put the future of U.S. energy security at a great disadvantage.

How Safe and Secure is SSP?

Wireless power transmission brings to mind a host of safety and security questions. How will wireless transmission impact people? Will this be a danger to airplanes or birds? Are buildings, bridges, or other structures at risk of harm from these transmissions? The answer to all of these questions is that SSP systems are designed to be safe, and no harm will come to people, birds, aircraft, structures, or anything else from these transmissions. In fact, these transmissions are not much different than those surrounding us every day.

Power transmission from the solar power satellite is generally through microwave transmission at a low power level. Although the wavelengths are the same as used in our kitchen appliances to cook food, the signal strength is much, much lower. The Federal Communications Commission (FCC), which is responsible for regulating wireless transmissions, notes that microwave ovens "should not be confused with the lower-energy, non-ionizing radiation" produced by low power transmissions. [11]

The U.S. Food and Drug Administration, one of the agencies tasked with protecting the public health, says "Microwaves are used to detect speeding cars and to send telephone and television communications." [12] Microwaves are also used for doppler radar systems.

Extensive research has shown that there is no damage to people, animals, structures, or anything else from these low power transmissions. This ensures that birds, airplanes, and anything else flying through the air will remain safe, as will people, animals, and structures on the ground.

Questions about cyber security of the satellites themselves, or of technical glitches, that might allow the power levels to increase are also important. The satellites will be designed in a failsafe way, to ensure that they are not capable of transmitting at an unsafe power level.

Additionally, there are concerns about cyber attacks disabling a transmitter or taking control and turning it off, cutting the flow of energy to a part of the world. We recently saw the cascading impacts when part of the Colonial Pipeline was shut down via a ransomware attack, the rising cost of fuel, the immediate shortage and panic-buying which increased demand for gasoline by 40% over the previous week. [13] As with cybersecurity at all levels, SSP systems will have to employ the most rigorous protective protocols available and build specialized protocols to update such safety measures on a regular basis.

Are There Open Legal and Regulatory Questions with SSP?

The current U.S. legal and policy landscape for SSP is ill-defined. Such lack of clarity could expose inventors and entrepreneurs to potential civil liability and to criminal prosecution. More likely, those individuals will continue working on other projects which don't bear the same potential personal and professional risks.

A key regulatory area is wireless transmission of power, which would fall in the jurisdiction of the FCC in America, and require coordinating globally through the International Telecommunications Union (ITU). The ITU serves as an international diplomatic unit where the nations of the world work together to identify which uses are preferred for various radio frequency bands. The ITU table of frequencies serves as a treaty for the nations of the world in transmissions that cross international borders. Wireless transmissions are mostly regulated with respect to the interference they can cause to devices or to other transmissions. Each nation remains responsible for regulating wireless transmissions within its own borders.

It will be important that the nations of the world recognize that wireless power transmission fits well within the standard, accepted framework and are fundamentally no different from signals from radio, television, cell phone, satellites, and other systems we use every day. Negotiations on the use of specific frequencies will need to take place, tests will need to be conducted to ensure no harmful interference or identify devices or transmissions that might be impacted. The ITU and the national regulators around the world conduct these studies regularly, and are well versed in this analysis. Moving existing users from desired frequencies may be challenging, but there is significant experience with that as well. The FCC has been clearing existing users from the C-Band (3.7-4.2 GHz) for future use in 5G communications. [14]

As we have become more aware of the environmental impact of individual activity multiplied across billions of people living their everyday lives, we are now investigating more than ever the potential harm that systems can create in unexpected places. As such, there are additional questions about environmental impact of power transmissions. Although we do not expect to identify negative impacts, we need to better understand if these power transmissions might alter the chemistry of the atmosphere, including the ozone layer, or otherwise increase climate stress.

Greater attention is also being paid to space sustainability. The environmental considerations for satellites are being expanded to consider orbital debris, light pollution, impacts of satellites re-entering our atmosphere, and other space sustainability goals. Solar power satellites will need to conform to all laws and regulations in place, and be designed to account for these emerging areas of interest.

Additionally, regulations and protocols will be needed on how SSP electric power will tie into the electrical grid. This might also be a challenge, as there are many stresses and disparate viewpoints about grid management. But the terrestrial solar tie-ins have eased the way, and the benefits of the system should encourage significant buy-in across America and the world.

How will SSP Enable our Future in Space?

Building large enough systems to serve global energy needs will require a significant amount of mass. When launching into space, the more mass, the larger the rocket, and the more costly. As discussed previously, developments in the launch industry have brought launch prices down dramatically. Eventually, however, it may make economic sense to use resources that already exist in space.

The geology of the Moon and asteroids are well-known, and the base materials needed to construct most of the satellites are available there. Mining on the Moon or asteroids could provide these base materials needed for most of the satellites, with electronics and other delicate or specialized components being launched from the ground. Plans for mining these materials, as well as the development of new techniques, are already underway. [15]

Enabling capabilities such as advanced in-space mining, in-space manufacturing, on-orbit autonomous assembly, assessment, and maintenance, would require advanced robotic systems – both autonomous and telerobotically controlled, and a capability to maintain, upgrade, and repair the robots.

Modularization of SSP components will mean that those components will also be available to use for other in-space infrastructure. It will also allow the scale of production, and cost savings inherent in that, to be benefit these other in-space infrastructure projects/needs.

These in turn would enable additional people in space. People who would live and work there – at first for a short time, then for longer and longer stretches. Eventually, individuals will go to one or more of these locations to stay – to make a home.

As we move from stations and bases into communities – it is self-evident that energy needs will be significant. Throughout human history energy, water, and the freedom to act and own are the base requirements for advancement, achievement, and growing societies. Human ingenuity is a boundless resource. At billions of years of clean power, the Sun comes in a close second. We need to tap into it for the long run, to continue and expand on our success as a species. The COVID pandemic is a dramatic warning sign that we are at risk to a single event, and these changes can ensure that such an event doesn't eliminate our species, our history, our technology, our capabilities, and our future.

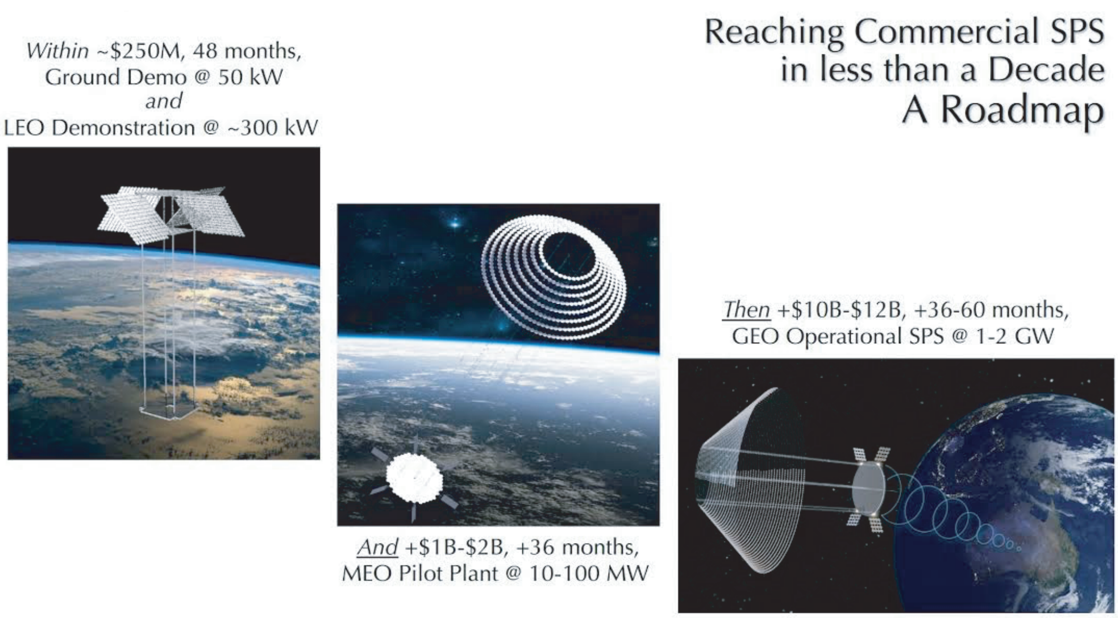
Policy Recommendations

Creating a Space Solar Power commitment at the national level, and implementing a directed research, development, and demonstration effort will be be costly and challenging, but America and all of humanity, will reap benefits vastly outweighing any expense.

Therefore, the United States should embark on a program, leveraging the full array of agencies and resources, to demonstrate SSP. Such demonstration should provide a pathway for a commercially sound approach and include international and private sector partners.

The following policy recommendations provide an outline for a strong approach that could successfully implement SSP as a major component of the national and global energy mix in the nearest term. The American government should:

1. Declare that the development and use of SSP technology is a key national goal and an integral component to meet our energy needs in the future.
2. Take a "whole of government" approach to SSP technology assessment, development, demonstration, and use.
3. Develop the necessary SSP technology and systems.
4. Deploy and use SSP and wireless power transmission systems.
5. Design SSP systems to meet the existing and potential future terrestrial commercial needs, as well as the NASA, DoD and commercial space mission requirements for government and commercial use.
6. Resolve spectrum management, space sustainability, and other regulatory issues.
7. Resolve operational security, cybersecurity, and other security issues.
8. Demonstrate SSP and WPT systems within space and from space to Earth.



Conclusion

While the authors of this paper are wary of grand policy declarations, a strong national commitment is needed for America to lead the world in Space Solar Power. Without such a commitment, other adversarial nations may have a clear path to control the energy production of the future. Or, without such a commitment, the world will continue to rely on fossil fuels for the next century or longer, maximizing the climate impacts until new reserves can no longer be found.

We do not think SSP is simple or easy, but it is clear to us that research, development, and demonstration of SSP in the near term is critical to the future of humanity. SSP is also enabling for space exploration and development, leading to communities of people living and working beyond Earth. We are closer than ever before in making SSP a physical reality and an economic reality. The reduction in costs for space launch and capable satellites brings us closer, and continuing reductions will get us to break-even faster than most suspect. The potential use of in-space resources to build large systems will reduce costs further and drive prices down while creating economic incentives to build more capacity quickly.

There are clear policies that must be engaged if America is to become a global leader in SSP. The authors believe the recommendations are clear, concise, and achievable. We hope policy makers embrace the opportunity and make the commitment to SSP for the people of America and of the world.

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Research Team

Tony DeTora
VP of Policy Coherence & Co-Founder

VP, Government Relations at Lynk Global, inc. & former Capitol Hill senior staff, space policy

John C. Mankins
BEI Advisor

President of Artemis Innovation Management Solutions LLC, and a Director of Solar Space Technologies, Inc.

Steve Wolfe
President & Co-Founder

Deputy Executive Director, Global Spaceport Alliance, and Capitol Hill veteran who served as executive director of the Congressional Space Caucus

Jonathan G. Thorvilson
Research Associate

BA in Political Science from the University of Colorado, and Masters degree in Space Studies from the University of North Dakota.

www.beyondearth.org
917.443.7240
swolfe@beyondearth.org