Space-Based Solar Power Satellite Systems

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Introduction

One of the unrealized potential uses of space systems that has been discussed and examined for nearly five decades is the tantalizing idea of creating solar power satellite, or what is most commonly now called space-based solar power (SBSP). The theory is that it would be possible to create such a system at geosynchronous orbit or perhaps at a suitable Lagrangian point that would be capable of beaming clean energy back to Earth on a 24 hours a day 365 days a week basis. This energy would be sent down to Earth using a suitable radio frequency or laser transmissions that could then be converted to electrical power using diodes placed within dipole antenna receivers. This energy could then be sent to locations where energy is most needed. Countries without large energy reserves, such as China and Japan, have accordingly been among those nations that have pursued some of the most active research programs in this area [1].

The economic importance of satellite telecommunications, broadcasting, remote sensing and space navigation is now well established. The satellite communications market, which represents about $150 billion a year in revenues, is today, however, the only true economic powerhouse as space industries go.

Some believe we might well be on the verge of creating in future years yet another new space industrial sector. This new space application has the potential to become another truly huge new space industry market. Clean and green electrical power from space is thus one of the aspirations of those seeking new commercial space applications.

In 1972 on the Voyage beyond Apollo this author had the pleasure to meet Dr. Peter Glaser, the father of what was then called solar power satellites, or Sunsats. Glaser advocated creating space systems that displayed a large number of photovoltaic cells that could be illuminated by the Sun not just during the day but on a continuous basis. Glaser advocated that this power be transmitted back to Earth in the microwave bands. One of the many highlights of this amazing cruise was to hear Dr. Glaser debate with English engineers whether RF

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transmission, or as the English scientists argued, perhaps lasers might be the best way to proceed. In the early 1970s petroleum was cheap. The world population was only 4.5 billion. At this time in history neither carbon-based fuels nor climate change were widely seen as looming issues. Thus solar power satellites were not seen as a practical nor cost-effective way to derive electrical energy, but rather something for the possible longer term future.

In only half a century the world has changed greatly. Earth's population has swelled to 7.5 billion and may expand to as much as 12 billion by 2100. Climate change and global warming are now major environmental concerns worldwide. It is possible to envision SBSP system designs that will, in the not too distant future, perhaps, be cost-competitive with carbon-based energy systems such as coal, oil, or nuclear power. Despite some health and environmental concerns, SBSP systems are largely seen as a "green" energy source that could be distributed to parts of the world where significant amounts of clean energy are needed.

NASA scientist Geoffrey Landis, who has spent years researching the technical and economic feasibility of SBSP systems, contributed an important idea to the field. He noted that one of the key challenges in many cities was not continuous supply of energy on a 24 hours a day basis but simply meeting peak-load requirements that are typically only about one-eighth of the total load requirement. Thus one might consider a role for SBSP systems would be to supply peak load requirements from a GEO orbit location to different cities as they encountered peak requirements. A phased-array or spot beam system could provide peak-load requirements to different cities on demand [2].

There are now safety standards for power beam density for SBSP system transmissions, and there are health standards for what level of power might be received by land-based or sea-based rectennas that are considered safe for receiving the transmitted energy. Most experts agree that RF transmission is safer than lasers and would have less of a problem of penetrating cloud cover.

There has been sufficient progress in the area of SBSP systems that a variety of national projects and even commercial ventures have begun to come forward to suggest that they could in coming years successfully deploy SBSP systems that would be cost competitive and would pose no health risks if designed and operated to current safety and health standards.

There have been several starts and stops by commercial ventures that have looked promising but have faltered for a variety of business, economic and technical reasons. At the outset the idea involved what was seen as a single giant facility that included massive solar arrays, the system to convert the power to be transmitted and the transmission system back to Earth and receiving system on the ground. Today SBSP systems are more frequently seen as coming in several different parts. These parts include low mass concentrators that focus the Sun's radiation so that a smaller unit of photovoltaic cells (or quantum dot) solar power generators would see the equivalent of many suns. In space there would be then be three key elements: (i) the solar concentrators; (ii) the photovoltaic power generators; and (iii) the unit that would convert the energy to a microwave or millimeter wave transmitter that would beam the power down to Earth. On Earth there might be several large-scale antenna systems (called rectennas) that could receive the radio frequency (RF) power at different locations and convert it to electrical energy at much lower frequency and transmit that power to urban transformers for distribution.

The logic of these systems and key economic calculations have for a long time focused on the ability of space-based systems to become cost-competitive with conventional electrical energy plants that are fueled by oil, coal, or nuclear-based power. What is important to note is that today this is only a part of the cost-analysis equation.

Tremendous progress is now being made with new types of Earth-based renewable energy sources. These increasingly cost-efficient electrical power sources include, among a growing number of options, solar (photovoltaic systems and soon quantum dot systems), hydroelectric, geothermal, wind farms, and even passive energy conservation systems such as better insulation and lighting systems. These ground-based renewable energy systems are all increasingly cost effective and are now developing apace. All of these renewable systems are not only becoming more cost-effective but are serving to reduce reliance on a consolidated energy grid that has positive implications in terms of resiliency. These are all key factors to consider with regard to the potential future of SBSP systems. Further when one considers the cost of coal, oil or nuclear-based energy systems, it is important to include the environmental costs associated with these, rather than conveniently ignoring them.

This chapter explains the current status of the most advanced solar power satellite system designs in space and for ground-based rectennas as well as the financial, economic, management and regulatory issues that still need to be overcome to move solar power satellites from engineering prototypes to actual operating systems.

From Early Design Concepts to Current SBSP Systems

The first concepts with regard to the possible development of solar power satellites came at the same time that there were also thoughts of possibly designing and manufacturing very large communications satellite platforms. In the 1970s and 1980s there were also very futuristic ideas of being able to carry out materials processing and manufacturing on the Moon. These included ideas that satellite antenna reflectors and solar arrays might thus be manufactured on the Moon. This would allow the communications platforms and solar power satellites to be built on the Moon and then “lowered” to GEO orbit with only the intricate electronics being manufactured on the ground and then added to these large and massive structures.

The logic of much of this thinking was that the launching costs for very large structures had remained quite high and seemed likely to remain so for many years to come. Launching materials or structures off the Moon with its modest gravity could open up major new opportunities.

The enthusiasm that came with the sending of astronauts to the Moon starting in 1969 gave rise to unwarranted enthusiasm as to what might be possible next. The president of Caltech predicted sending astronauts to Mars in the 1980s. The sky was no longer the limit. Instead, though, the United States and much of the spacefaring world restricted its vision in the decades that followed to projects like the space shuttle, low Earth orbit space stations, and modest progress in the field of space.

Only in the last few years has enthusiasm for space and the "we-can-do-everything-that-we-dream-of" mentality begun to return to space enterprise. In the preceding chapters, the remarkable new achievements in satellite communications, remote sensing, space navigation, meteorological satellites, and on-orbit servicing have certainly been aided by lower cost launch vehicles. Further the prospect of reusable launch vehicles and new launch options for cubesat-sized spacecraft have helped to foster the rise to Space 2.0 initiatives and entrepreneurial outside-the-box thinking. But all of these initiatives were able to proceed without innovations in launch vehicles. Indeed some of the small sat innovations may have even been aided by higher launch costs. This is to say that of all of the space applications discussed up to this point space-based solar power is uniquely in need of significant cost reductions in launch costs. In essence, better and less costly launchers are essential to achieving financial viability for Sunsats.

Current Efforts to Design and Develop Space-Based Solar Power

There are many national space agencies, research organizations and commercial space organizations that are pursuing new and viable designs for space-based solar power systems and various types of technology that could contribute to the development of these. The various technologies that are under consideration or development include the following:

- solar concentrators with lower mass with increased reflectivity
- protective systems to preserve the performance of photovoltaic cells
- higher performance photovoltaic cells such as those operating in the ultraviolet range
- quantum dot technology to improved power generation capabilities
- material processing in space to generate refined materials to make solar cells
- additive manufacturing techniques to create solar cell arrays in space
- improved, lower cost and reusable launcher systems
- improved diodes and dipole RF antennas for rectennas
- means to reduce interference between SBSP systems and communications systems
- improved robotics for the deployment and repair of SBSP systems
- phased-array systems to allow distribution of RF signals to rectennas more efficiently

There are today a wide variety of concepts that have been proposed, such as the Alpha SBSP systems. This design was developed by Dr. John Mankins of Mankins Space Technology, Inc., who led the NASA research effort in this area for a number of years. (See Fig. 8.1.)

Another concept approach comes from a NASA design study that tends to validate the three parts approach of: (i) a modular set of low mass yet large aperture solar concentrators; (ii) photovoltaic cell power generators; and

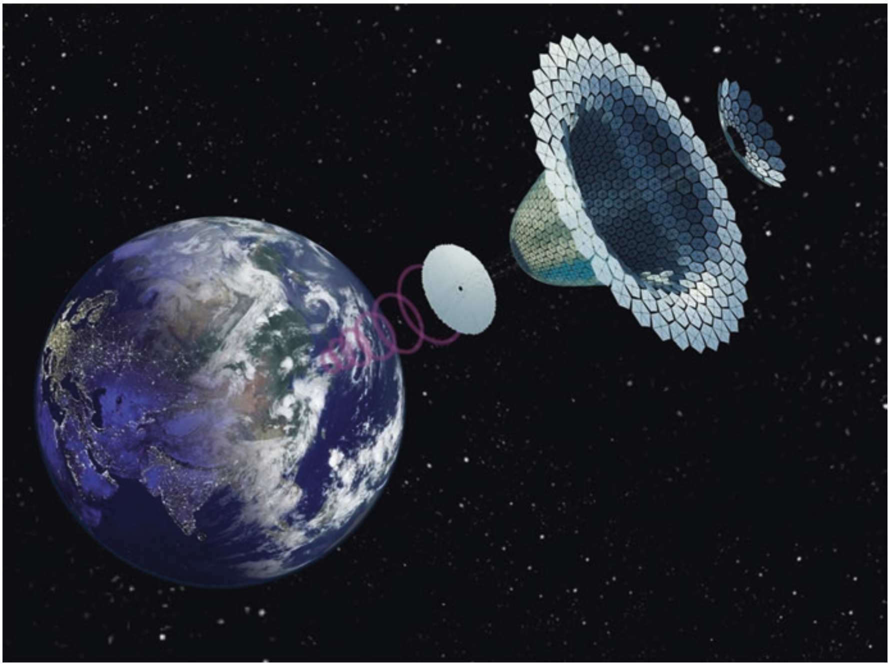

Fig. 8.1 The Alpha space-based solar power system. (Graphic courtesy of John Mankins of Mankins Space Technology, Inc.)

(iii) RF transmitters. These concentrators could allow the solar cell power generation system to be able to be subjected to the equivalent of seeing many dozens of suns. (See Fig. 8.2.)

A recently released design from Space Energy, Inc., a commercial organization, claims it will deploy a space-based solar power system that in many ways has similarities to the NASA design in terms of having being modular [3]. (See Fig. 8.3.)

Peter Sage, the CEO of Space Energy, Inc, has expressed optimism that their system can be fully deployed and operational by 2025. He has been quoted as saying: "This is an inevitable technology; it's going to happen. If we can put solar panels in space where the Sun shines 24 hours a day, if we have a safe way of transmitting the energy to Earth and broadcasting it anywhere, that is a serious game changer." The problem is other commercial organizations that have gone before and claimed that they could sell space-based derived solar power at competitive rates but have not been able to deliver on their aspirational statements.

The great challenge for these systems is not only to be competitive with oil, coal and nuclear-based electrical power systems but renewable energy sources as well. The costs of terrestrial solar cell units and wind turbine electrical generators, for instance, have fallen sharply in the last decade. Solar cell systems, in particular, have fallen in price by a factor of 77% and are expected to drop a similar amount in the future as the cost of

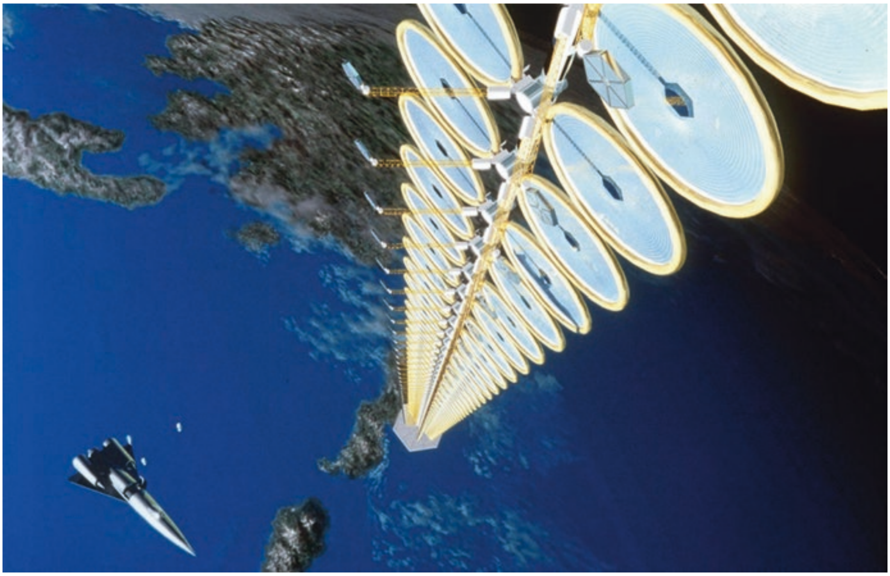

Fig. 8.2 NASA concept for a space-based solar power (SBSP) system. (Graphic courtesy of NASA.)

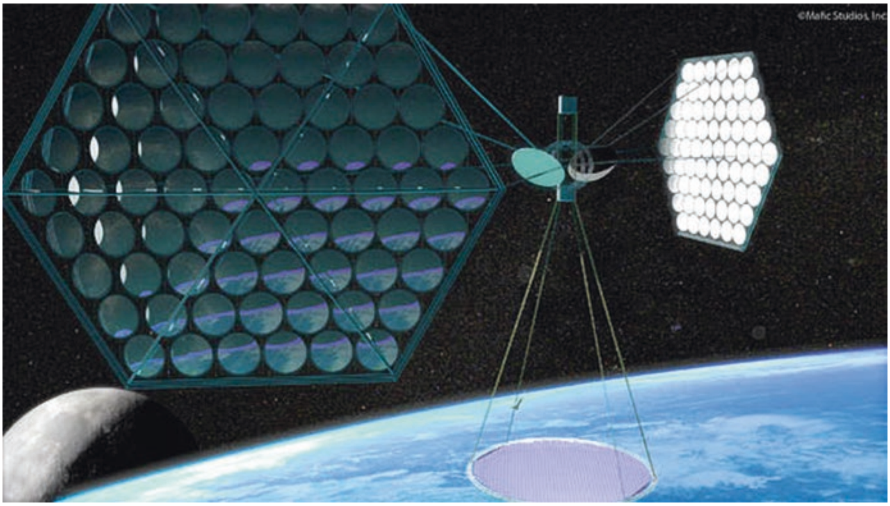

Fig. 8.3 The proposed design by Space Energy, Inc. (Graphic courtesy of Space Energy, Inc.)

energy storage systems also continues to fall. This seems to be especially the case with the Chinese manufacturers entering this highly competitive market for both solar cell power systems and more cost-effective energy storage systems [4].

Ground Systems for Space-Based Solar Power Reception

The key to the operation of SBSP systems on Earth will be in the design and operation of what are called rectennas. This is actually short for “rectifying antennas.” It is usually envisioned as a large series of dipole antennae configured as a network over a large circular area thousands of square meters in size.

Each of the dipole antennas would be configured with a radio frequency (RF) diode connected across the dipole elements so that it would ‘rectify’ the alternating current (AC) to induce a direct current (DC) power flow. This power flow from each diode could then be consolidated and transmitted to a transformer within an electric grid network for distribution to users.

The rectenna would spread out over a large area that would include thousands of such dipoles, each with diodes arranged so that they would convert on a consistent basis the incoming RF transmission into DC power for the entire area. The RF transmitting antennas out in space could be configured as spot beams. This would allow the sunsat to distribute its transmissions to different but quite specific locations that were in proximity to where the power was actually needed. The reason that the power would be transmitted in this manner is to avoid concentrating it and creating a form of death ray. A very high intensity beam would be dangerous to anyone in an aircraft or helicopter flying through the beam. In addition to health concerns about the radiation levels being too concentrated, there is also the additional concern that there could also be reflected energy returning power back up to space that would create harmful interference to satellites in orbit.

The invention of diode-based rectennas is attributed to William Brown, an American engineer that came up with the idea in the mid-1960s and was issued a patent in 1969. Rectenna technology can be used in the context of wireless power transmission. Other potential applications could include maintaining platforms or even keep a helicopter or other type of aircraft aloft. The most important application in terms of space systems would be to develop rectannas to receive RF transmissions from space-based solar power systems.

Research in this area is currently focused on the ability to create so-called devices that would operate not at the RF level but in the nanometer frequency range of infrared and light waves. Ultrafast and miniaturized diodes that are scaled to operate in these frequencies could, in theory, also be used to convert light directly into electricity. This type of device is called an optical rectenna, or nantenna. High efficiencies up to 70% conversion might be attained, in theory, but efficiency has so far been limited, even though working optical rectennas have now been demonstrated [5] (Fig. 8.4).

International Initiatives in the Space-Based Solar Power Arena

SBSP is being actively pursued by Japan, China and India in particular, but there are also certainly significant and ongoing efforts in the United States, in Europe and Russia, among others. There are several international efforts to share

Fig. 8.4 Illustration showing a rectenna for SBSP reception plus an electrical power transmission system to an urban center.

information with regard to the development of new technology in this area. Perhaps most notable is the ongoing effort to share research and development in the SBSP field among the following organizations: the University of Science and Technology Beijing, the China Academy of Science and Technology (CAST), the Indian Space Research Organization (ISRO), the Indian Institute of Space Science and Technology (IISST), the Japanese Aerospace eXploration Agency (JAXA), several Japanese universities, and others.

In 2008 Japan's Diet passed its Basic Space Law. This law established space solar power as a national goal. As a response to this law the Japanese space agency (JAXA) has developed a roadmap, or plan, for its ongoing efforts in the development of SBSP technology and systems. It has also encouraged commercial SBSP ventures. JAXA is to some extent unique in that it has developed goal-oriented programs built on applications and uses defined by its national legislature in its Basic Space Law. Thus JAXA has developed roadmaps and even timetables in such areas as national and international broadband services, remote-sensing applications, and now sunsats as goals to achieve. JAXA has designed its ongoing technological and applications programs to coincide with these national social and economic objectives. This has tended to make JAXA more applications and uses driven rather than technology driven. All space agencies have strategic plans, but JAXA roadmaps are more driven by clearly defined national economic and social goals than the other agencies [6].

In 2015 the China Academy for Space Technology (CAST) showcased their roadmap to a 1 GW commercial system at the International Space Development Conference (ISDC).

India has carried out extensive reviews of their current energy production capabilities and what their projected increased energy needs will be, especially in the case of sustained economic growth rates in the range of 5%

per annum up to 8% per annum. Even a sustained growth rate averaging 7% per annum would result in the need for nearly 1,400 gigawatts capacity by 2050. This would require an increase in capacity of more than a hundred times India's current capacity. India has committed to greatly increasing its domestic energy production based on terrestrial renewable energy sources, but has sought to work with other nations to explore the possible development of SBSP systems as a supplementary source of energy.

The result of India's study was to conclude that the pathway to finding an economically viable way to deploy any truly meaningful sunsat capacity would require the development of reusable launch system that could lift needed payloads to orbit with an efficiency of $100 to $200 per kilogram. This also assumed a reusability factor of 100 to 150 times for the launch systems. In short, India and ISRO in particular proposed that an international consortium would need to commit to such a development enterprise and that India's prime contribution would be in the development of new launch systems that would be required to deploy the needed photo-voltaic (PV) cells to orbit. Currently the cooperative agreements to work on new sunsat systems is limited to China, Japan and India, and the needed breakthroughs in the launch systems and the sunsat technology have not come close to being attained [7].

Other Reasons for the Development of SBSP

There are actually several reasons why there seems to be continuing interest in the development of space-based solar energy. The first and foremost reason is the favorable environmental effect. It has been claimed that sunsats are a clean and reliable way to green and renewable energy that is reliably available 24 hours a day, 365 days a year. Countries such as China and Japan, for instance, have projected their future energy growth needs and have not been able to find a viable way to meet all their requirements, which continue to grow. One study, conducted by China Academy of Engineering (CAE), has projected that it will have a 10.5% energy gap in coming years and that SBSP systems may be one of the means to meet these needs [8].

Further, if energy needs are viewed from the perspective of national disasters, which in the past have led to the shutdown of energy-generating plants, then sunsats can be seen as a means to respond to power loss during emergencies. Further, this could also be seen from the perspective of national defense. It is important to have a source of supply if international energy sources are cut off or limited. In such a case it would seem vital to have sunsats as a potential source of supply.

Launch Systems and the Viability of Space-Based Power Systems

The viability of sunsats in the future heavily depends on the technical design of key components such as solar concentrators; the PV cells and their resilience to solar radiation; other similar technologies such as higher-efficiency quantum dot systems that can convert solar radiation into transmittable RF power; improved terrestrial rectenna design; and processes for finding large areas where these ground systems can be deployed. It is perhaps equally true that the development of improved and greatly more cost efficient launch systems are just as critical to completing the economic equation for designing, fabricating and deploying such systems in space.

In the chapter on launch systems, the significant progress that is being made in developing new and much more cost effective systems for deploying new space systems in orbit will be discussed. There has been significant progress in developing launch vehicles that can be used many dozens of times. These objectives are high on the priority list for new Space 2.0 firms such as SpaceX and Blue Origin. The current launch systems that are being designed for repeat missions, however, can only be used around 25 times. This is short of the studies that have suggested that as many as 100 reuses might be required to get the launch cost figures down to those projected to be needed – at least in some of the costing studies.

The key fact to note here is that the sunsats and the cost effective launch systems are integral to each other. They go together like a horse and carriage. You can't have one without the other.

Policy and Regulatory Concerns

The deployment of sunsats or SBSP systems will not only require the development of new technology and significant new capital investment but also give rise to a number of policy and regulatory concerns as well. The International Academy of Astronautics study of this subject, entitled "Assessment of Space Solar Power: Opportunities, Issues and Potential Pathways Forward," was conducted and reported on in 2011. This study suggested that the issues to be addressed and resolved included the following [9].

- What are the key wireless power transmission (WPT) beam health and safety considerations, and how should they be addressed in terms of health and safety standards and regulatory oversight?
- What spectrum allocation and orbital management procedures should be adopted to accommodate this service in terms of transmitting energy to Earth via radio frequency (RF) transmission or via other spectrum such as via laser transmission? (Currently the allocations that might be considered are 2.4 GHz and 5.8 GHz bands.) [10]
- What are the possible space debris impacts and related considerations in terms of debris mitigation and end of life removal from orbit?
- What might be the potential "weaponization" of the wireless power transmission systems associated with sunsats and what international agency might address these concerns?
- What is the best strategy and process for addressing the international coordination of these type systems in terms of their development and operations? [9]

The above listing is really only the start of the "what, why, where, how and who" of the issues to be considered. Here it is truly a case of "the Devil being in the details." There is a need for clarification within the International Telecommunications Union (ITU) as to the exact process that will be followed with regard to allocation of the exact frequencies that would be used for Regions 1, 2 and 3 or globally – most likely in the microwave band – or downlinking of the high-powered RF transmissions from a space-based system as well as for telemetry, tracking and control. There is likely to be a need to establish the power transmission limits that might apply, the process for assignment of exact orbital locations or characteristics for positioning of particular sunsats, and the process for frequency and interference coordination of such sunsats with communications satellites and other spacecraft.

There are literally dozens of issues, processes, standards and policies yet to be established. Will there be national licensing processes as well as registration of such sunsats with the ITU as well as with the United Nations, as required under the Registration Agreement? Further there are questions as to the liability agreement concerning how such systems are launched, owned, deployed and operated. This becomes particularly important if the sunsat is constructed in orbit and involves processing, manufacturing, assemblage, integration and quality assurance testing.

Conclusions

Virtually all of the space applications addressed up this point in the book involve well known practices and commercial applications where a good deal of precedent has been set as to how governmental licensing, due diligence and international collaborative processes should be followed. This is not the case so far as SBSP systems are concerned. Will such sunsats be operated as commercial projects by a single owner, by some sort of international partnership, or perhaps by some new type of international structure that follows such possible examples as an Intelsat, an Arianespace or some other model? There is truly a long list of health and safety standards still to be developed. Likewise there is a need for appropriate procedures with regard to registration, ownership, RF and orbital location coordination and more.

The bottom line is that there is still much more to develop and prove with regard to the viability and reliable performance of the technology. Notably missing are the needed launch capabilities as well as the technical and operational design of the SBSP systems themselves. There remains the need to validate the cost effectiveness of any currently deployable SBSP systems. This cost-effectiveness needs to be demonstrated not only in terms of competitiveness against traditional coal- and oil-powered electrical generation plants, but also against the ever more cost-efficient terrestrial renewable energy sources and energy storage systems that have increased significantly in the past decade, which are currently anticipated to increase in economic efficiencies by similar degrees in the coming decade as well.

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