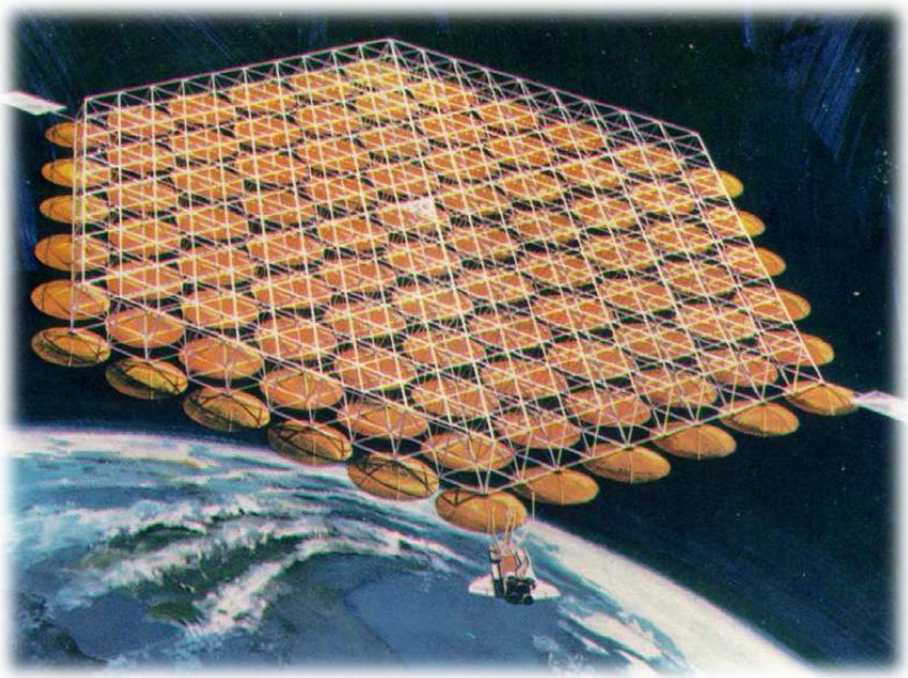
SPACE BASED SOLAR POWER



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Industry and Technology Assessment

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Abstract

Modern society functions on the back of abundant amounts of cheap

energy. In 2010 alone, world energy demand increased by over 5%, supported by large increases in consumption by China, India, and Russia. As the rest of the world continues to industrialize, an unavoidable effect is increased demand for energy. There is a demonstrable need for increased and varied sources of energy. The weaknesses in depending too much on limited suppliers have been frequently demonstrated, including the 1970 OPEC oil embargo, and the recent Chinese embargo on thorium. There is an urgent need to not only increase the total available supply of energy, especially from environmentally friendly energy sources, but also an urgent need to diversify the sources of energy for national and global strategic security. The sun is the largest such untapped resource.

Space Based Solar Power

INDUSTRY AND TECHNOLOGY ASSESSMENT

Executive Summary

Unlike traditional sources of energy such as oil, gas and coal (the fossil fuels), SBSP doesn't involve the burning of fossil fuels, which have been shown to cause severe environmental problems and global warming. SBSP is also more efficient than traditional solar power, as sunlight is almost five and a half times as strong in space than it is on the surface of the earth [1], as it does not have to interact with the atmosphere, weather, and day/night cycles. Space based solar power would be able to run almost continuously, with only short periods of time (of at most 75 minutes during the equinoxes [2]) when a satellite would be in the Earth's shadow.

Some important aspects have changed that could lead to SBSP evolving from a futuristic fantasy into a current, plausible reality. First is the advent of private space launch companies. The most famous one is SpaceX, which aims to launch objects into space at a fraction of the current costs. The other is the wireless revolution. Such widespread use has allowed wireless power transmission to take dramatic leaps forward, and as a consequence, provided a plausible solution to the issue of transmitting power from space onto the surface of the Earth.

In this report, we introduce some of the technological aspects of SBSP. However, we will be focusing on laying down the economic groundwork for SBSP. We obtain linearized trend data for various factors that affect the marginal cost of SBSP (primarily solar panel efficiency, orbital transport costs, and energy demand and cost). We determined that it is actually infeasible to begin work on SBSP, as the marginal costs do not provide an adequate annual return for us to recommend SBSP.

Unfortunately, we determined that large capital and R&D costs are required for SBSP to occur, further decreasing the likelihood of SBSP from being large scale feasible. Without dramatic disruptive technology or large, governmental investments, SBSP will not be feasible as a mainstream source of energy until at least 2040.

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Perspective

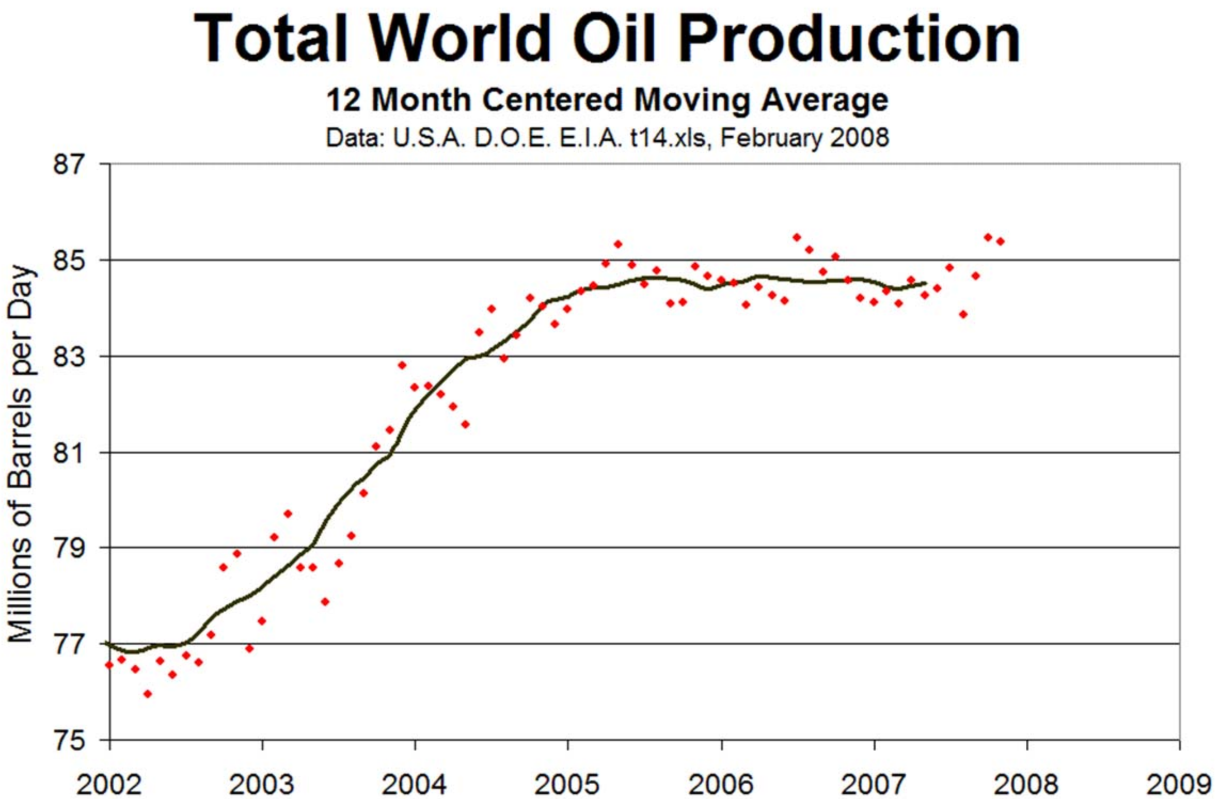
History

From antiquity until now, and into eternity hereafter, the sun around which our planet orbits has provided a constant source of heat and light, both of which were already harnessed, but which mankind has only recently begun to exploit as energy to power an increasingly electronic world. By the 1970s it was widely accepted that fossil fuels were a non-renewable and steadily dwindling resource. With the realization of pollution that occurs from fossil fuels, various avenues of alternative energy have been explored, and it is evident that terrestrial solar power's vulnerability to both weather and the day-night cycle would require needless investment in power storage. In 1973 Peter Glaser patented a long ranged wireless power beaming technique using microwaves and large antennas, known as rectennas. This spurred a series of studies on the political[3], economic[4], and technological[5] implications of the technology, which generated some interest until a change of administration in 1980 at NASA, Congress, and the Department of Energy shelved the project. 19 years later, NASA revived the project for review with the SERT (Space Solar Power Exploratory Research and Technology) program, which had the goal of conceptualizing and enabling the technology to build gigawatt-class SBSP systems while reducing associated roadblocks such as launch costs and transmission technology. By 2003[6], published advances in wireless power transmission technology, as well as commercial sector development in launching, increased the interest in SBSP such that startup ventures emerged around the concept, centered around three companies in particular – Solaren, PowerSat, and Space Energy. By 2009[7] a deal, the first of its kind, was signed between major electricity provider PG&E and SBSP startup Solaren to provide

200kW of solar power against baseload consumption in California from space. Solaren is currently focusing on actualizing a 200kW pilot program, while the other two companies are focusing on accumulating government partnerships to support a long-term profitability plan, or radical new avenues in R&D that will reduce deployment cost by billions.

Future Energy Sources

Recent studies regarding “peak oil,” the time when the world oil supply reaches its highest volume before it declines, suggest a time frame between now and 2016, and multiple scenarios predict a 10% reduction in production by 2030 [8]. Oil makes up 29% of the current energy supply [9]. While these numbers suggest that oil will decrease at 0.005% per year, its actual decrease will not be gradual, but instead be a sudden precipitous drop over the course of only a few years [8], not giving the market enough time to develop a suitable alternative without having a destructive effect on the global economy.



Coal, also makes up 29% of the current energy supply. “Peak coal” is estimated by academic sources to be reached in the next few years, and have been reduced to 50% of peak values by 2047 [10], though significant technological improvement in mining and refining low quality coal may reduce some of the effects.

Producing 25% of the world’s sources of energy, natural gas is the only resource that is not expected to peak until 2020[11]. However, natural gas is not commonly shipped over ocean lanes, leading to a natural gas crisis currently in North America, as domestic (US and Canadian) production is not enough to meet demand, even with the use of environmentally destructive “shale gas” and other unconventional natural gas resources. North American peak natural gas could occur as early as 2013 [12]. Including the widespread use of environmentally destructive practices, North American gas production will only increase by 5% by 2025 [13].

Combining this data with data for total consumption gives us the following table[14]. The projections were all constructed using the standard Hubbert method, after which the overall changes were linearized and then extrapolated to 2025, as shown in the table below.

Energy Source	% change by 2025	Absolute change (as percent of current supply) by 2025
Oil	-7.5	-1.9%
Natural Gas (OECD)	+5%	+1.1%
Coal	-24%	-5.9%
Total Fossil Fuels	-9.5%	-6.7%

Average Projected Energy Demand Growth	Absolute change (as percent of current supply) by 2025	Necessary growth in renewables +nuclear (percent of current supply) by 2025	Necessary annual Growth in renewables + nuclear
1%	+15%	22%	9.3%
2%	+32%	39%	12.8%
3%	+51%	58%	15.6%

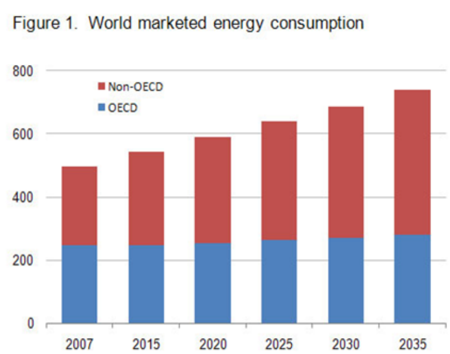
4%	+73%	80%	18.5%
5%	+98%	105%	20.0%

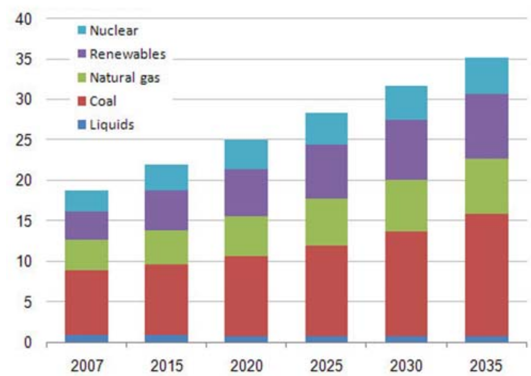
Nuclear and renewables, discounting traditional biomass, currently accounts for 8.8% of the world energy supply. If we assume a low, basic growth in energy demand, by year 2025 there will need to be a 32% increase in energy supply. If we project a loss of 6.7% by 2025 from fossil fuels, there needs to be an amount of 38.7% of the current energy supply that comes from nuclear and renewables. This amounts to an increase of 12.8% per year from nuclear and renewables alone. While on the other hand, a 4% annual increase in energy demand would lead to a necessary 18.5% increase in the renewables and nuclear.

Nuclear energy is approximately half the size of the renewable energy sources. Considering the difficulties there are in disposing of nuclear waste, and the recent problems with the nuclear facilities in Japan casting doubt on the safety of nuclear energy, it is unlikely that nuclear energy will be able to meet this increased demand. Furthermore, though currently renewable energy is increasing at a rapid rate, of around 20% over the renewables (mainly hydroelectric power) as a whole [14]. This indicates that there needs to be growth of a new source of energy in order to match such demand. Furthermore, as supply is not linear, but is instead expected to have sharp changes due to the Hubbert curve, a prepositioned alternative source of energy may have much to gain.

According to studies by the United States Energy Information Administration, from 2007 to 2035, world net electricity generation is projected to increase by 87 percent, from 18.8

trillion kilowatt hours in 2007 to 25.0 trillion kilowatt hours in 2020 and 35.2 trillion kilowatt hours in 2035. In OECD countries, where electricity markets are well established and consumption patterns are mature, the growth of electricity demand is slower than in non-OECD countries, where a large amount of potential demand remains unmet. Total net generation in non-OECD countries increases by 3.3 percent per year on average, as compared with 1.1 percent per year in OECD nations. Total demand is expected to increase at 2 percent each year. World renewable energy use for electricity generation is projected to grow by an average of 3.0 percent per year and the renewable share of world electricity generation increases from 18 percent in 2007 to 23 percent in 2035.





Technological Background

Space solar power is thought to have several advantages over other forms of alternative energy, particularly over terrestrial implementation of solar power. The chief general advantage is that the SBSP satellite is that it is relatively isolated, neither taking up space on Earth nor being vulnerable to degradation from nature. As will be addressed in following sections, deploying SBSP satellites do release small amounts of pollution, and the effect of beaming large amounts of energy through the ionosphere is not yet adequately documented. However, these effects are generally agreed[3] to be overshadowed by the potential benefits, including the risk of hydroelectric damming, petroleum storage, coal mining, and nuclear waste. SBSP is thought to be especially attractive against terrestrial solar power for the reason of persistence. Land based solar panels are illuminated for only the daytime, subject to seasonal variation in daylight, as well as the filtering of a large amount of solar energy through the atmosphere by the time it reaches the land based panel no matter its efficiency. By contrast, an SBSP satellite is illuminated for 99% of the day on most days, and 95% of the day even on seasonal equinoxes[2]. Furthermore, SBSP satellites receive 450% [2]additional solar energy than terrestrial solar panels, which couples particularly well with recent advances in metamorphic solar cells that exceed the theoretical limit of conversion efficiency from solar power.

Space based solar power is comprised of two major technologies which have been experimentally demonstrable in some form since the 1980s[15]. These are architecture of the satellite and receiver module, and the means to beam energy back to Earth. Both architecture and transmission technology have one main challenge each. For architecture, a major challenge is the cost of infrastructure, both of launch costs associated with deploying the massive SPSB satellite and of building a land receiver rectenna that may be on the order of kilometers. For transmission technology, the challenges are more dire. Three current paradigms are radio frequency, laser, and microwave beaming techniques, but all three suffer loss through Earth's atmosphere, and may indeed harm either the atmosphere or signals from other satellites. Moreover, the transmission technologies of all three techniques are fairly nascent, and there are some difficulties in packaging power on the order of MW or GW into a coherent beam. Currently, startup ventures in SBSP are either in the process of developing solutions, or have already patented innovative technologies that address the many issues of SBSP. As such, the burgeoning SBSP startup sector is currently dominated by whichever corporations have viable plans to address the technical hurdles.

Setting

Key Players in SBSP

Solaren Inc., founded in 2002, is one of three startup ventures in SBSP that have met with some success. It is the first and the only company which has signed a deal with a major electricity provider, PG&E, to provide power from SBSP, which they intend to implement by 2016. Solaren believes it can provide SBSP-sourced electricity, even from its pilot project, at only an unspecified "small amount" more than California's projected energy cost of $0.13/kwH in 2016. From an interview with a Solaren employee, their current priority is to meet the implementation goal for their pilot system, and to develop their technology for the future in order to meet MW and GW power delivery goals.

Space Energy, founded in 2005, is composed of a large number of individuals with a business background. As such, they have done much to publicize the attractiveness of SBSP, including their relations officer Peter Sage speaking at TEDx. In fact, they are exploring many possible issues related to SBSP that other groups are not, such as the competitiveness of SBSP with relation to nuclear power, and the importance of international cooperation with regards to establishing a meaningful SBSP foothold in space. Space Energy has an $80 million grant from the Chinese government, and has given several presentations to Japanese authorities on SBSP.

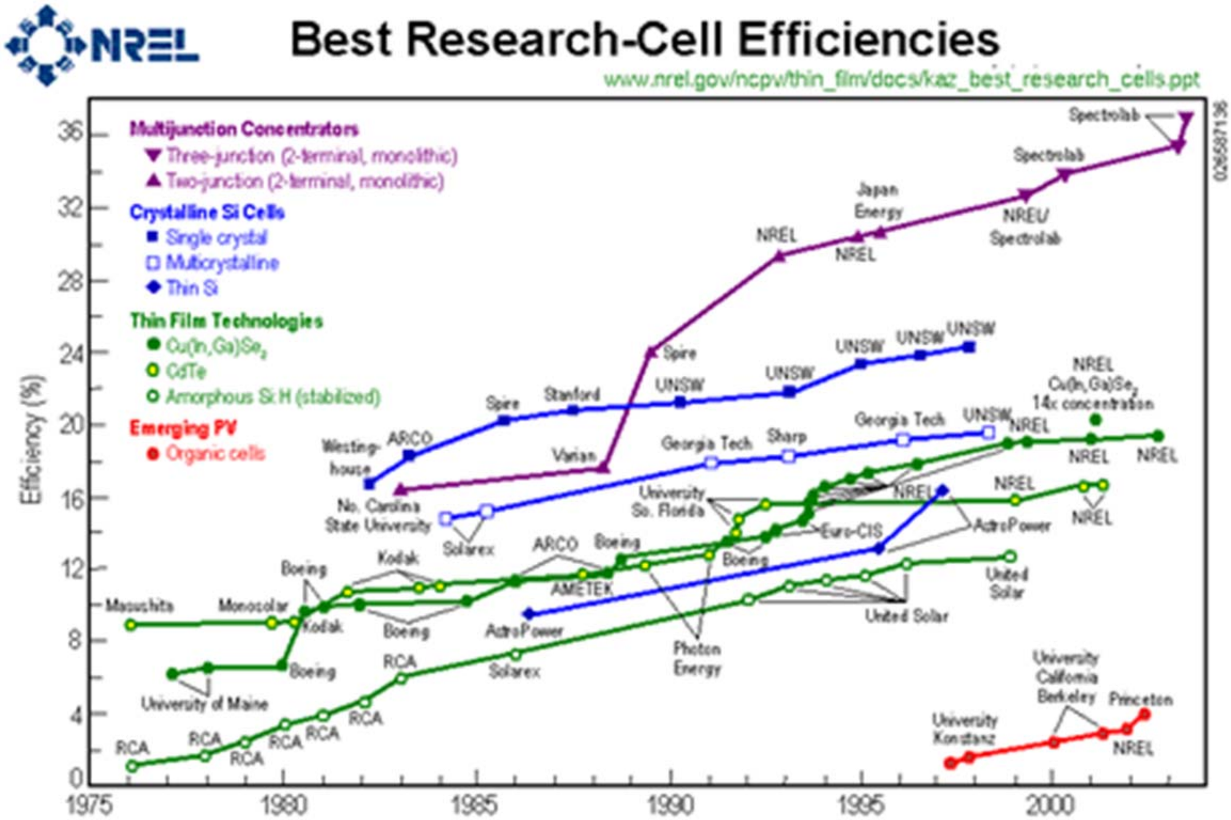
PowerSat Corporation, founded in 2006, places great emphasis on the necessity of technology to implement SBSP. They possess a large number of trained scientists and are focusing their efforts neither on an immediate pilot program nor an energy company contract. Instead, PowerSat touts an impressive patent portfolio which contains surprising and innovative solutions to both the issue of architecture and transmission. Their chief patent libraries are Brightstar and SPOT, respectively a “cloud” system of small but cooperative SBSP satellites, and an ion thruster system powered by the very same solar power the satellite harvests that draws from virtually no external fuel. An interview with PowerSat reveals that they intend to add a third patent collection, which will focus on increasing the reclamation efficiency of the land receiver rectenna towards energy beamed down from space. When combined, PowerSat will maneuver itself into a superior technological position to implement an effective SBSP network system.

Economic Analysis

Feasibility

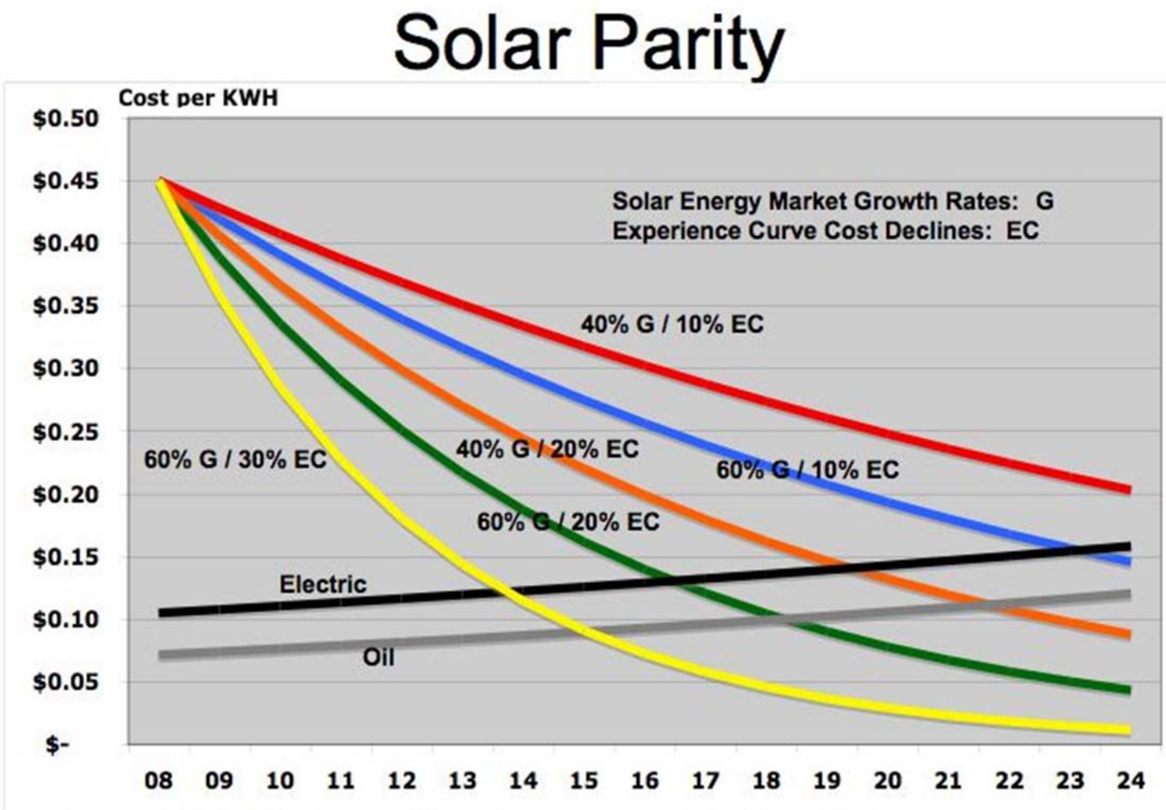
Using accumulated data sources from the internet, over a wide range of online web sites and discussion forums, we obtained general estimates of output per surface area of solar panels, the mass per area, and the mass of a laser or microwave transmission setup. The launch costs are derived from data on SpaceX’s new launch system, as well as assuming a

0.8 reduction in launch costs per year, as corroborated by the interview with Cornelius Zund[16].



[17]

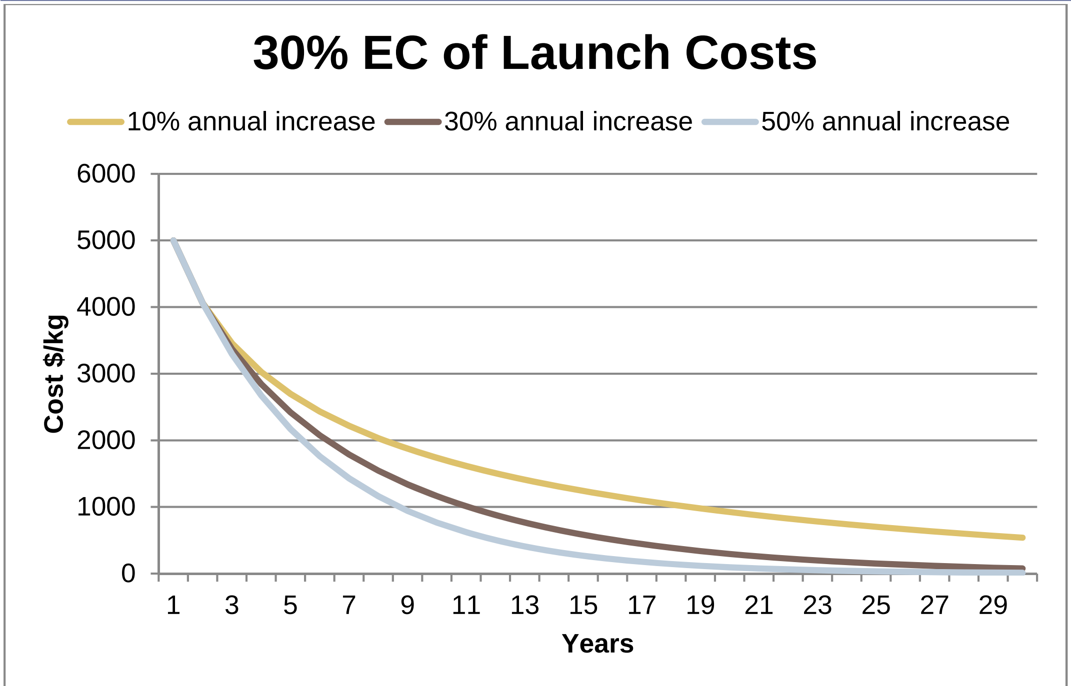
We take the chart of solar cell efficiency to obtain a trend for solar panel efficieny over time. Linearizing the trend from the beginning to the end of the chart, we come out with a 6% annual increase in solar efficiency. We then notice that recently, there has been a high trend in efficiency gains, so we assume that a 10% annual increase is obtainable. Furthermore, an actual efficiency change has to be of form where there is a decrease in inefficiency per year. Thus, from our current efficiency rating, we can obtain a 95% annual decrease in inefficiency.



Source: Department of Energy, Green Econometrics research

[18]

From Green Econometrics, they derived that a median estimate is to have 40% market growth in solar energy, and a 20% experience curve. Utilizing that data, when linearized, we find that there is a 10% per year reduction in cost. Noting similarities among the high tech fields, which during the initial periods are highly correlated between efficiency and reduced costs, this confirms our 10% efficiency annual gains, or in other words, a 95% yearly inefficiency reduction.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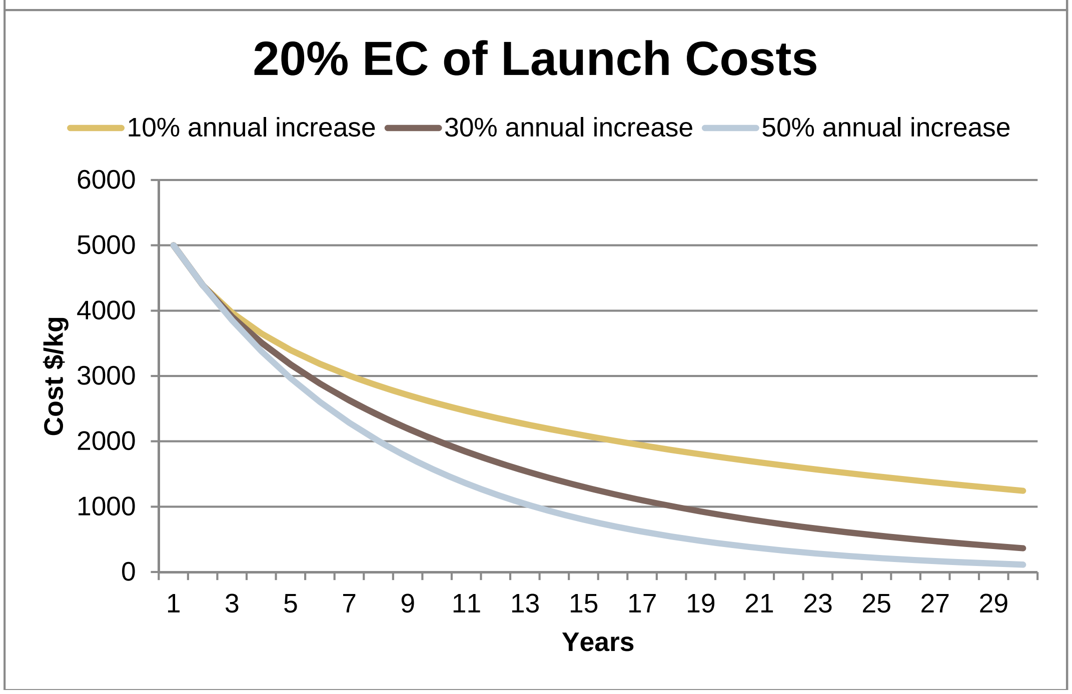
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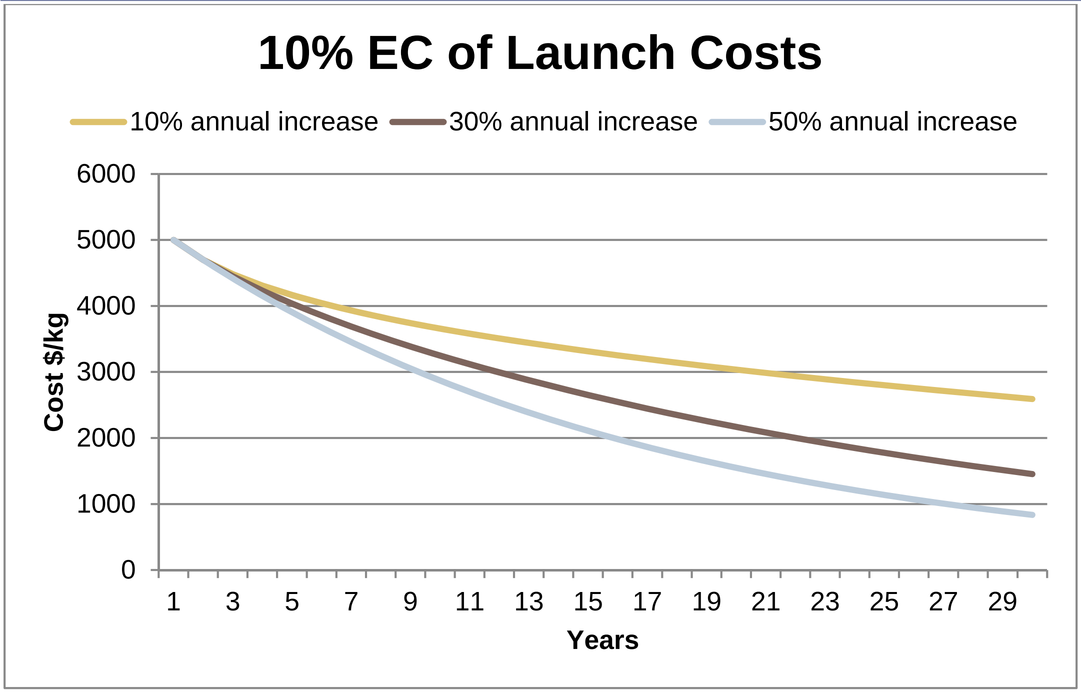
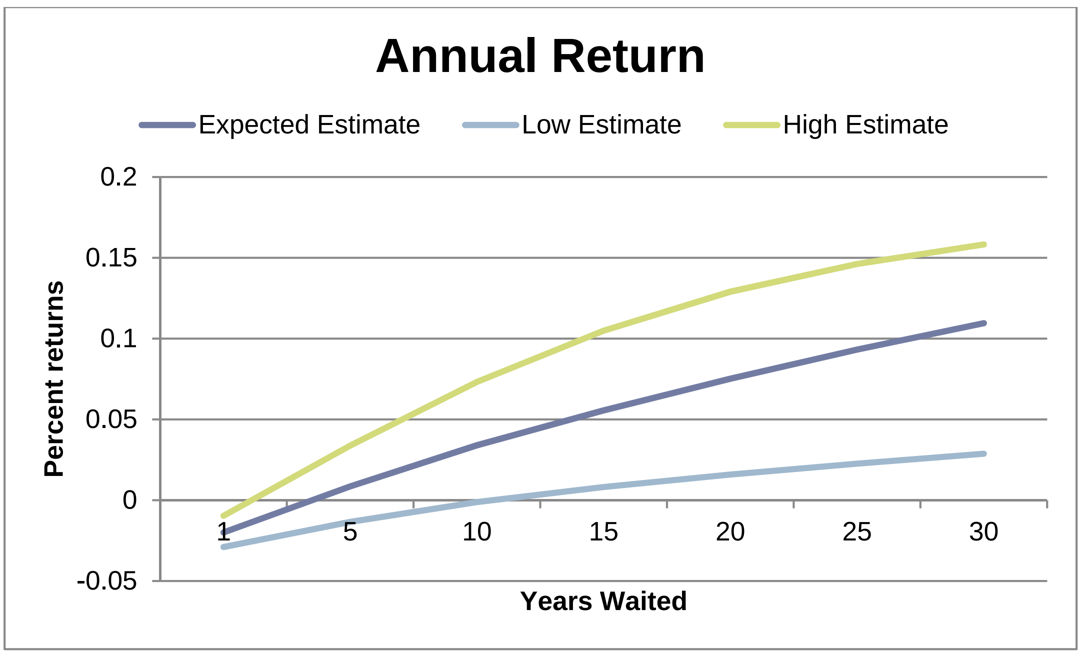




Using data from previous studies and our own linearized estimations, we are able to obtain a chart for annual returns on investment. This only supposes that the only cost incurred are putting solar panels up in space. All other costs are completely ignored, such as fixed costs, capital costs, etc. Even the costs of putting up a transmitting array, or construction is ignored. In other words, the costs shown here are similar to marginal costs, if all the space and ground infrastructure was already set up. We are only looking at “when is it even remotely feasible to begin thinking about SBSP as a mainstream source of energy.” We see from the graph that in fact, for a median estimate, even waiting thirty year is not enough to reach a 15% return. Since we are discounting the roughly 80% of the costs from other sources, 15% is the minimum to begin considering SBSP.

Near Term Judgement

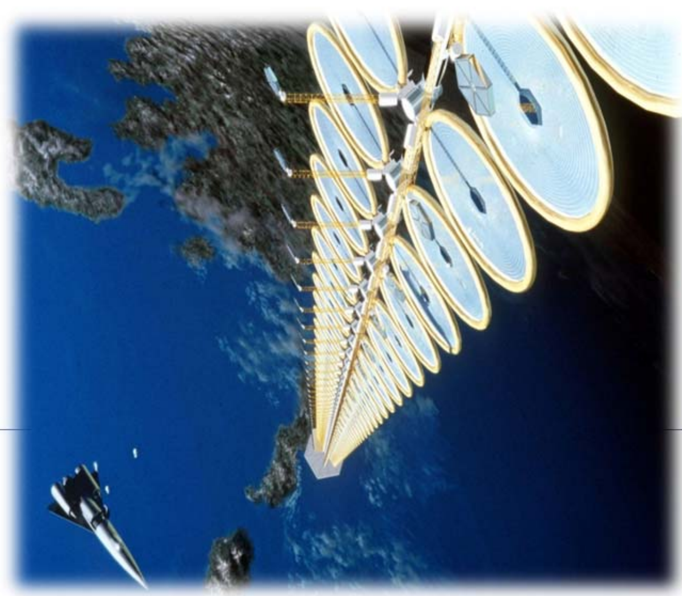
Right now, SPSP is not viable as a mainstream source of energy. In fact, even when accounting for the most optimal effects, we would need to wait at least 30 more years before beginning a large attempt at adopting space based solar power.

In order for SBSP to be feasible before then, we would require some sort of disruptive technology in orbital launch, such as a space elevator. Another case might be where the Earth’s atmosphere suddenly prevented more of the sunlight from reaching the Earth, increasing the efficiency gains from using SBSP.

Technology Analysis

Architecture [19]

<u>Middle Earth Orbit (MEO) Sun Tower</u>: It is composed of a 15 km long structure with 340 pairs of solar collectors. At the bottom of the structure is a circular 300-m transmitter that would beam

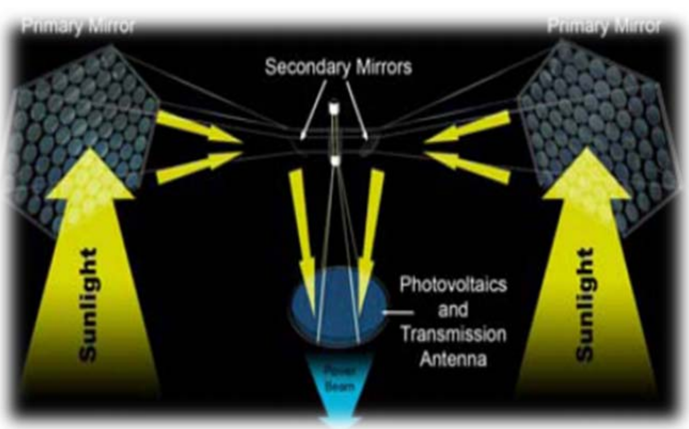


power to the Earth. The satellite would be in a circular equatorial orbit. This is the standard option.

GEO Sun Tower: This architecture is similar to that of the MEO Sun Tower. However, it will have a geostationary Earth orbit (GEO) instead. The geostationary orbit allows a single satellite to supply power continuously to a given receiving station on Earth. This makes this architecture more versatile. Also, the total power will be greater due to the reduction in scanning loss. Due to the geostationary orbit, this structure will be deployed at a greater distance from earth, which will reduce encounters with space debris.

Clipper Ship: This architecture has pointing transmitter array with long mast-like solar collectors . The "Borealis" orbit that is used is sun-synchronous and elliptical; therefore, the collectors will not have to rotate to track the sun. Although, power cable lengths are much shorter than that used on other designs (15 km long Sun Tower), transporting this structure into space and scanning to beam down power are more difficult.

GEO Heliostat/Concentrator : This architecture uses a geostationary orbit. This GEO Heliostat consisting of a mirror or system of mirrors that tracks the sun and reflects light onto a power generator/transmitter array. This



architecture allows the Heliostat to be smaller and shorter than the Sun Tower architecture. This helps with power management and distribution.

GEO Harris Wheel: This geostationary uses a central photovoltaic power generation/transmission system, and a wheel of co-orbiting mirrors. Each mirror controls its orientation to reflect sunlight onto the central power generation system. The mirrors move in a circle about the generator/transmitter. Like the GEO Heliostat, the GEO Harris Wheel is smaller and shorter than the Sun Tower architecture. This helps with power management and distribution.

Lunar Station: This architecture consists of arrays of photovoltaic solar collector/microwave transmitter panels on the ends of the Moon. Therefore, one array will always be exposed to sunlight and all arrays

have line of sight to the Earth. Power will be available only when the Moon is in direct line with the receiving station

Transmission[5]

What allows Space Based Solar Power to be viable is increased, rapid advancement in wireless power transmission technology. There are two primary options for transferring power from the spacecraft to a receiver: microwave and laser. One key factor that must be considered to select the optimum technology is conversion efficiency (solar to microwave or laser, and microwave or laser to prime electrical power at the receiver). Another factor is the transmission losses due to attenuation, diffraction, scattering, etc.

Laser based technology is generally considered to be less viable for space based solar power because of the inefficient conversion from DC to laser to DC again. Also the absorption from the atmosphere makes laser based technology a poor choice.

The microwave technology consists of three parts: the transmitter, beam control, and receiving rectifying antenna (rectenna). The transmitter takes the DC produced by the solar panels and beams it in the form of microwaves. The beam control accurately points the transmitter towards the receiver and adjusts the beam amplitude/ phase so that the system can transmit energy with high efficiency. Finally, the rectifying antenna receives the microwaves and converts it back to DC. Some draw backs of microwave technology is that the transmitter and receiver are much larger than that of laser based technology. However, microwave based technology can be converted much more efficiently and will experience less loss during transmission. Using some laboratory results, and a mixture of experimental technology and current technology, currently we can hope for 45% transmission efficiency to convert energy from DC to DC when transmitting from space to Earth [5]. It is also suggested that longer wavelength be used to decrease transmission loses. However, this could have undesired interference with existing communication systems.

Potential

Markets and Applications [20-22]

There is a significant amount of research suggesting that consumers are willing to pay a premium for energy from renewable or 'green' sources. Such willingness is usually correlated to the extent of education the participants' have received regarding environmental issues, as well as typical socioeconomic factors. Experiments and even reliable survey data are much less forthcoming in suggesting a specific amount that a consumer might pay as a premium. While some of our interviewees proposed a premium of up 15%, this seems optimistic based on our survey scholarly sources. It seems significantly more realistic to propose a 5% price premium for green energy. The typical US household currently pays 0.10 dollars per kilowatt-hours (kWh), therefore even an optimistic 10% premium would result in an electricity price of only 0.11 dollars per kWh. Given that SBSP can, at least initially, only produce a relatively small amount of energy, this premium would have little impact (in absolute dollar terms) on our overall estimates. To wit, the price of SBSP electricity is so large that the impact of such a premium on our economic models is negligible.

In order to drive sales prior to the intersection of the electric experience curve and the SBSP curve on thegraph above, we consider selling SBSP power to niche markets. In particular, these would be

costumer for whom electricity is otherwise very costly, due (at least in part) to an inflexible demand curve. Such a costumer could be US military forward operating bases (FOB) in dangerous and remote areas.

While this is a niche market, it is by no means insignificant. The military is already spending significant amounts to secure energy for its bases, resulting in high cost exposure to world fuel prices as well as substantial loss of life in vulnerable fuel transportation convoys. Consider Afghanistan, where the Pentagon estimates that fuel for base generators has a fully loaded average cost of $400 per gallon. In a typical FOB generator configuration, the base outputs approximately 52897 kWh per day using 4880 gallons of fuel. Thus, the cost of electricity is approximately 36.90 dollars per kWh. This represents a 3700% premium over the average US household cost of 0.10 dollars. Therefore, a military ready SBSP system could be deployed in short order and still result in significant savings to the military. A scenario to accomplish this could be the deployment of a folding rectenna on a single military truck. Once in place, there would be no ongoing supply chain risk. In addition to cost savings, a SBSP system would result in saved lives and more effective allocation of military personnel and resources. A major difficulty presented by this scenario, however, is that the rectenna would have to be well secured while simultaneously ensuring that energy from the satellite does not have destructive effects on the surrounding area (i.e. the rest of the base) or the base's communications systems. Therefore, while we believe it has great potential, this niche application still requires significant investigation before it can be recommended for development.

Scalability of Deployment

Currently, there are approximately 70 launches per year. [23] A successful SBSP mainstream program would require a dramatic increase. The locations and availability of launch locations becomes an issue. However, that is beyond the scope of this report.

Counterindications

Political and Social Considerations

Due to the high energy transmitter that it will utilize, space based solar power could potentially be in violation of international space treaties. In 1967, the Outer Space Treaty was signed by the United States and other world powers. One of the key issues addressed by this treaty is space based weapons. The Outer Space Treaty bans the placement of nuclear weapons and other weapons of mass destruction in space or on any celestial body. This could become a serious issue for space based solar power because of the potential for the transmitter to become a dual use weapon. Additionally, the newly proposed Space Preservation Treaty could severely hinder the implementation of space based solar power, as it would ban the any kind of weapon from being placed in space. In addition to political issues, there may be social disapproval of having a potential weapons system in space

Business Strategy Proposal

We have confirmed the following initial Hypothesis

There is a need for sources of energy other than what we have now.

There is a strategic need for alternative sources of energy. Furthermore, our analysis indicates that is unlikely renewables will continue to grow at a pace fast enough to be able to meet such a need.

Energy demand will only continue to grow.

Preliminary information suggests that consumption will continue to grow at 2-4% yearly.

A SBSP platform can generate a significant amount of energy.

All existing architectural options are for large scale energy generation. There are strong parallels with the nuclear industry, as a SBSP platform will generate large amounts of energy and will run constantly.

The platform and infrastructure can be constructed using current and near future technology

Preliminary interviews indicate that this is the case. Most of the necessary technology is already available, though untested in space.

There is no current planetside infrastructure to support SBSP.

The necessary rectenna stations are not available, as before now there was no need for large scale rectenna stations.

No space treaties prevent private space platforms from being constructed

A quick glance at the major space treaties confirms the fact that only nuclear weapons are not allowed to be used in space.

Launch costs will decrease at a rate of 10% per year [16].

We have obtained an experience curve for launch costs through interviews and other research

Solar panels will be more approximately 125% more effective in space.

After factoring in transmission loss, due to the increased intensity, we find this to be true.

SBSP main costs lie within infrastructure and launch. R&D will be same magnitude or less of infrastructure and launch.

We find this to be false. From interviews, everyone agrees R&D will make up bulk of requirements.

There is a green premium

Research and interviews state anywhere from 2% to 15%.

Niche markets will be willing to pay a premium of over 300% for energy.

Through research and interviews, we find that the military is willing to pay 3700% premium.

We have yet to confirm the following, or have included new hypothesis

The price for energy will continue to grow

The use of environmentally unsafe practices to extract natural gas will be allowed.

New technology will allow the efficient use of “low quality” coal.

Wireless energy transmission will not harm the atmosphere (25% as strong as noon sun on ground, but other long term effects may still occur)

SBSP is environmentally net positive when including the negative effects of space launches (space launches are 3% of CFC emissions, but we have not calculated emissions saved. There are also too many different kinds of rocket fuels with different effects)

It is possible to increase launches from approximately 15 (in US) to around 120.

The objective is to create a space based solar power system that will be able to provide enough power to offset a more traditional power plant. Due to the developing nature of space based solar, most short term goals will be to progress in research and development. Within 10 years, the business should send a preliminary pilot satellite into low earth orbit to determine the viability of the incorporated wireless power transmission technique. Longer term goals will concentrate on making the company into a viable alternative energy provider and encouraging further investment into the industry. In 25-30 years, the business should to launch a satellite that could satisfy the needs of the niche markets such as energy generation for forward military installations. Shortly after, the business should follow up with additional launches to create a satellite capable of outputting 0.5-1 GigaWatts.

The success space based solar power will be determined by the ability to decrease cost, with much of this depending on the development of rocket launches. For space based solar power to be viable, the frequency of rocket launches needs to increase and the cost per kilogram needs to decrease. Another major issue is the design of the space based solar power platform. Primarily, the wireless power transmission systems need to be developed so that there is acceptable DC to DC conversion efficiency. This also affects the necessary payload and structure of the space based solar power platform. Methods of assembly in space, system architecture, etc. must also be developed. It will be difficult for the business to be profitable early on since it will lack a product and be mainly in the performing research & development.

The development of infrastructure and the deployment costs will require a large amount of funding. Space based solar power is high risk and there is no guarantee that there will be acceptable returns. Because of the long development cycle, investors will not receive any returns until several decades later. Therefore, investment groups/ venture capitalists are unlikely to fund space based solar power. The company will need to be assisted by the government investment. Currently organizations such as NASA, the Japan Space Agency, and the Chinese government all appear to have interest in developing space based solar power. The business will have to continue to run on government grants until it can launch a satellite for niche markets. After this point, the business will start receiving income and there will be greater confidence to invest into space based solar power technology.

Conclusions

From our preliminary analysis and interviews, we discovered that currently SBSP is still in the “early” stages of the S-Curve. The amount of future capital and R&D needed to simply begin the process of SBSP is in the billions, and are all early stage.

Most of the technology used in this report is what NASA would term below Stage 6. Much of it is experimental, in laboratory settings only, or has yet to be tested in a space environment. There could be considerable technical roadblocks to ensure all parts work for 30 years in space. As such, there are significant R&D problems that must first be addressed.

The cost of space launches are another potential roadblock. If the price per kg does not decrease at a significant rate, large scale, capital intensive projects such as SBSP will most likely not be feasible. However, disruptive technology such as a space elevator can quickly make SBSP a realtiy. A further roadblock will be the potential dual use of any space based platform. A satellite which can beam power at a receiving station can also beam power at any arbitrary location.

Large, urban infrastructure is built on an abundance of (relatively) cheap energy. If SBSP is successful, it has the potential to be part of the new frontier of space, which is currently opening up. There is significant and large potential in this market, especially as our analysis shows that current sources of energy are not enough to meet growing demands within the next 30 years.

While hard to estimate, we believe currently that SBSP is not feasible for the next 30 years. There must first be a large decrease in launch costs, and significant adoption of solar technology before SBSP would be a plausible large scale energy source. Efficiency levels are still not yet at a level where the large added cost of a space launch can justify SBSP. Furthermore, the difficulties in large scale wireless energy transmission is paramount, and have large scale demonstrations have not yet occurred over significant distances. We have also not yet seen a large boom in large scale wireless energy transmission that would allow us to project an efficiency trend for this technology.

We conclude that it is still too early for SBSP, barring any large scale technological disruptions within the next 30 years.

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Appendix- Interviews

Dr. Feng Hsu – Space Energy – Senior Vice President of Technology – 30 minutes

A comparison was drawn between Space Based Solar Power and nuclear energy. As Hsu was formerly from the field of risk management in nuclear energy, many of his analogies are from that field. The first call was followed up, resulting in two sessions. Overall, Dr. Hsu was more interested in discussing the political and societal merit of SBSP than the specific technologies that his company is pioneering. In Dr. Hsu's opinion, nuclear power maximizes a short term gain but pays for it in long term disadvantages, including cleanup, waste, and limits on exporting nuclear technology to places that may need it the most. Interestingly, Dr. Hsu predicts a 8-12% green premium following peak oil and given the Fukushima disaster, which he believes will greatly shift policy away from favoring nuclear energy. In the ensuing "gap," he believes SBSP can attain a more favorable position. Moreover, he cites that nuclear reactors can never be selectively built away from seismically active regions, and that terrestrial solar power works in the North American climate, but not in the humid climates of Asia and third world countries. Finally, he believes that affordable SBSP will become available far in advance of any form of break-even fusion power. As such he cites a 50-year profitability plan, which involves tanking a short-term loss in the billions in exchange for long term profit and being better positioned for future generations. His company has partnerships with China and the ESA, and is intending to expand upon the technologies that will hit the public domain over the next few decades in order to realize their SBSP system, a process he calls "spiral" innovation.

Solaren – Johnathan Marshall – Media Relations Officer – 20 minutes

Solaren's Johnathan Marshall is immediately evident as a seasoned spokesman of SBSP. He and his company's technical staff have 20 years of experience in aerospace. According to John, the post 9/11 reality has exacerbated the problem of peak oil, driving prices even further in a ripple effect that has had lasting implications. Alternative energy commonly uses a water medium, often boiling water and taking advantage of water's high thermal capacity. Nuclear, some coal, hydro, and solarthermal solutions all fall into this category. However, John cites a 30% absolute capture efficiency using these methods, and in addition, the reliability of all of those forms of alternative energy are suspect given their complex and interconnected infrastructure between sourcing, maintenance, generation, and actual delivery. Meanwhile, his company boasts of a 90% transmitter conversion efficiency from solar energy to RF waves. An approximate plan is to use a 1.5kW/m^2 array at 1300 mile low earth orbit for a mobile receiving device for niche or military frontline base applications, or higher altitude geostationary orbit for a dedicated receiving station. His company has secured partnerships with Boeing and Lockheed, for the possible purpose of mounting folding rectennas on cargo and passenger planes flying at an altitude of 30000 feet. They have possession of technology which allows their satellite to automatically seek the greatest exposure to high intensity sunlight with auto-correction to maximize capture efficiency in space. Solaren has 30 year profitability plan and has ties with NASA, the ESA, and the DoD as part of their strategic power subgoal. In relation to their agreement with PG&E, they intend to field a 200kW pilot program within the '11-'20 decade, and thereafter a 10MW, followed by a GW-class power system in each following decade.

PowerSat – Aaron Lindenbaum – Public Relations Officier – 10 minutes

PowerSat is the most technologically advanced of the three SBSP firms. Currently they are leveraging and perfecting two major patent libraries. The first is Brightstar, a system of possibly hundreds of small, cheap SBSP satellites with small rectennas similar to cloud computing. Each Brightstar satellite only provides 100kW of energy via an RF transmission that can be received by mobile receivers on the ground where a boost in the energy supply is needed the most. Alternatively and most remarkably, Brightstar satellites can couple energy to each other in order to send a much more powerful transmission of energy on the order of GW to a single destination, such as an immobile receiving station. Brightstar ensures that each individual satellite is lighter, easier to build, and more justifiably fundable. In addition, the system has great resilience and redundancy even if some Brightstars are lost. The second technology is SPOT, which saves the fuel weight of launches by 66%. Individual Brightstars can be launched either by a reusable "cannon" or very cheap boosters to only a 3000 mile low earth orbit. Then, PowerSat has developed an ion thruster system that uses collected solar power to boost the satellite into geostationary orbit. This same ion thruster can also be used for course corrections in space. Using these two technologies, PowerSat claims to be saving billions of dollars on deployment costs. They also have a 30 year profitability plan, and are planning to build a solid baseload power infrastructure both on Earth and in orbit. As such, they are sinking almost all of their money into R&D, with 10 year milestones. For the remainder of this decade, they intend to develop another set of patents pertaining to the reclamation efficiency of the ground receiver rectenna. In the next decade, they will begin to make launches and build their orbital control infrastructure, and finally in the third decade, they will actually build receivers, which they anticipate will be much more effective by then due to their research and other advancements.

Caltech – Dr. Harry Atwater – Applied Physics – 15 minutes

Professor Atwater is a physics professor who has great interest in solar panel technology, although he questions the effectiveness of putting solar panels in space. The panels already show a gradual loss of efficiency over time at 300K, whereby the panel elements gain more resistance to current, and the carrier recombination rate which drives the light to electricity conversion slows. On a sun-seeking panel that is always lit by light 125% brighter than on Earth, the increase in temperature can dramatically shorten the lifespan of the panels. In addition, using second or third generation thin-film and metamorphic panels is a gamble on mechanical stress. Deformation due to launch forces or the process of assembly can dramatically influence the effectiveness of these fragile cells. Professor Atwater recommends using "shaved" metamorphic cells. Shedding certain layers, such as the germanium layer, can decrease the cost by 20% and reduce the weight by up to 94% (if you shed every layer but one). The efficiency of metamorphic cells is approximately 41% on the ground, but he anticipates it will be higher in space. With bigger panels, the satellite will have bigger wings, and suffer more micrometer hits which are commonplace in space. As such, sustainability is a grave issue.

Caltech/JPL – Dr. Dmitrios Antsos – Electrical Engineering – 10 minutes

Dr. Antsos is a JPL native who is also a guest professor at Caltech. His specialty is communications, and he questions the ability to transmit raw power through the atmosphere using techniques otherwise developed for communications signals. All three startup companies seem to be planning RF transmission systems, because the RF transmitter has been maturing since the 1940s, and laser or microwave power are inadequately documented. However, Professor Antsos cites the difficulty in modulating a MW or GW power signal. It would require bulky components and the reliability would be questionable if frequency domain performance is a concern. Although the startup companies seem to be eschewing microwave and laser methods, RF can still have an effect on the ionosphere, although few experiment have been done on exactly what effect it will have. At worst, it could interfere with RF communications from other satellites, coupling noise power into their data-loaded RF transmissions when beaming. At best, Dr. Antsos estimates 20 years before microwave technology is mature enough to beam raw power from space. Because of the amount of uncertainty on how beaming this much power through the atmosphere will affect meteorology and other transmissions, NASA is instead looking into using SBSP technology in the case of satellites beaming power to each other. Future satellites may not come with their own solar wings, leaving more cargo space for vital equipment while the satellite receive power from pre-ordained collector SBSP satellites. In addition, on the moon or Mars where the atmosphere is more negligible, SBSP beaming onto the surface is less of an issue.

Tom Nuget Jr – Lasermotive – Founder

A discussion on wireless power transmission. Lasermotive is in the wireless power transmission business, though only for supporting unmanned aerial vehicles as opposed to SBSP. We discussed efficiency issues, though he was reluctant to give exact figures. Scaling problems were apparently not a significant issue. He did not have any specific, useful information about applying the technology to SBSP as it is not his field, though it is theoretically possible.

Cornelius Zund – "Financial and Organizational Analysis for a Space Solar Power System" – Author

We discussed the issues that Space Based Solar Power faced. We discussed in detail how they were able to come up with various figures and estimates for development, construction, launch, operation, and R&D costs. He related to me part of the extensive research he had done on the subject. Most of his figures were derived from interviews his team had conducted. We were able to obtain the industry estimate of the experience curve for orbital launches, as well as the minimum estimate from aeronautical industries.

Unfortunately, his team faced a shortage of time, and his figures had various weaknesses, which we discussed in various detail.

He estimates, from sources within the European Space Agency (ESA) state that an 20% Experience curve can be expected, with a minimum of 10% from similar industries. Furthermore, capital costs will be almost 90% of the final cost.