THE BUSINESS CASE FOR POWER GENERATION IN SPACE FOR TERRESTRIAL APPLICATIONS

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WHY SPACE ENERGY?

The present paper sheds light on a sustainable power source that has been studied by NASA since the late-seventies: the Solar Power Satellite (SPS)[1], a system which taps solar energy in outer space and transmits this energy to reception stations on earth. The concept of SPS systems was first idealized by Dr. Peter Glaser in 1968, amidst the Cold War and the Space Race. The main goal of the SPS concept is to take advantage of the readily available solar power that strikes the earth around the clock and, independently of seasonality and other intra-atmospheric issues, generate energy uninterruptedly in space to be beamed to earth for terrestrial applications. The main benefit of solar power satellites is the ability to generate electricity without causing endogenous problems on the surface or the atmosphere of the earth, i.e., it is a truly exogenous power source.

The motivation for this study is presented in the next section, which focuses on putting energy security issues in perspective. The section also analyzes the current flawed global model of energy generation and the fact that economic growth is highly dependent upon a country's ability to expand its energy generation capacity. The endogeneity of currently available power generating technologies is discussed. Evidence is presented to support the main argument, i.e., that all of the existing power generation options, whether fossil-based or renewable, are inherently endogenous to the Earth. Therefore, all available energy sources depend upon and, in certain cases, aggravate, rather uncertain long-term environmental conditions for their power generation capability to perform adequately in steady-state.

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1. "Satellite Power System Concept Development and Evaluation Program." National Space Society, last modified September 15, 2010, http://www.nss.org/settlement/ssp/library/doe.htm (hereafter cited as *NSS*, *SPS*).

While achieving short-term the goal of partially avoiding the worsening of environmental conditions, renewable energy sources still face a great deal of skepticism. Critics have argued that with rapid worldwide population growth, real estate will not be as easily available in the future, which might threaten the sustainability of solar power plants, the so-called solar farms. Scholars have also expressed their skepticism against wind energy, arguing that on-shore wind farms are undesired by most people, and cite bird mortality as a major shortcoming of this source of sustainable energy[2]. Some economists have also argued that biofuels have been forcing agriculturists to produce fuel instead of food in what in effect is a natural cannibalization of agricultural goods destined for eating, mankind's major source of sustenance. These economists have said that if this trend continues, the current number of undernourished people, which amounted to an estimated 925 million people in 2010, will continue to increase[3]. Besides, perhaps further exacerbating endogenous problems on the surface of the planet, all of these renewable energy sources have one weakness in common: they depend upon local environmental conditions. Windmills depend, for instance, on the seasonality of wind gusts; solar power depends on the availability of sunshine; biomass, on a combination of frequency of sunshine and frequency of rain. This means that there is an inherent uncertainty regarding the power production capability of these resources, which may further increase the risk of blackouts, thus increasing the needs of coal, oil, or gas-fired power plants to supply the lacking demand for power that might take place as a result. Additionally, this results in a circular, non-logical solution for a complex equation, as its result, i.e., the improvement of environmental conditions,

2. "Windmills are killing our birds." The website of the Wall Street Journal, last modified September 7, 2009, http://online.wsj.com/article/SB10001424052970203706604574376543308399048.html (hereafter cited as *WSJ, Windmills*).
3. "2010 World Hunger and Poverty Facts and Statistics." World Hunger Organization, accessed September 19, 2010, http://www.worldhunger.org/articles/Learn/world%20hunger%20facts%202002.htm.

which is one goal of the CleanTech or Green Products industry, ultimately depends on one basic variable, i.e., those very environmental conditions in order to achieve the desired results. A characterization of today's energy landscape is presented in the next section, which provides detailed data, which motivated NASA's study of the Solar Power Satellite as a means to overcome obstacles currently faced by other green energy systems.

After this main motivation for SPS has been thoroughly discussed, and the logical flaws in the current energy generation model are illustrated, focus is shifted to presenting the technological possibilities for space-based solar power. The third section provides information on architectural concepts and the methods for capturing the solar energy in space and beaming it to Earth, in an attempt to shed light on how some of the main technological concerns for the development of such an innovative energy generating concept could be addressed. Following this technological characterization of solar power satellites, an economic viability assessment model is introduced. Sensitivity analyses are presented, pointing to possible combinations of the most influential variables, and how these impact the financial base-case model. Possible future scenarios are then studied, demonstrating the potential of SPS concepts depending on different stages of technological advancement. Political viability is discussed in the fifth section, which focuses on the need for joint action among countries around the world for space-based solar power to become a reality. Finally, concluding remarks are presented. Special focus is given to SPS's unique characteristics of being the only existing power generating concept that is completely sustainable due to the exogenous nature and ready availability of the virtually infinite solar energy that strikes the earth atmosphere every day.

CONTEXT

In the end of the 90s, the American Physical Society issued a statement regarding its long-term view of the Energy Situation in the USA. From their point-of-view, the USA should have adopted a very aggressive plan to cut their consumption of oil then, although the oil costs back then were still very low (in 1996, for example, one barrel of crude oil cost less than US$30). Their assessment showed that low-cost oil resources outside the Persian Gulf were being depleted very rapidly, increasing the likelihood of sudden disruptions in supply[4]. The recommendations of the APS to improve the energy consumption scenario in the USA included the diversification of investments in energy research and development, as well as policies that promoted efficiency and innovation throughout the energy system. The next subsection will detail the energy problem with focus on the USA.

Current Issues

Energy Security

Access to increasingly greater amounts of low-cost energy has become fundamental to the functioning of modern economies. However, the uneven distribution of natural energy resources among countries has led to formidable vulnerabilities both from the supplier and the consumer sides. Threats to energy security include political instability of several of the major global oil suppliers, the cartelization of energy supplies, the competition over energy sources, attacks on production facilities, as well as accidents and natural disasters[5].

4. "Energy: The Forgotten Crisis." American Physical Society, accessed October 3, 2010, http://www.aps.org/policy/statements/96_2.cfm.
5. "A New Security Paradigm." Foreign Policy Journal, last modified September 14, 2009, http://fletcher.tufts.edu/news/2009/09/opeds/Mylrea-Sept14.shtml.

Since APS issued the statement on the Energy Situation of the USA in 1996, a shift has been noticeable in the pattern of US oil imports. Non-OPEC countries are now responsible for a larger portion of the oil imported by the US. Exhibit 1 presents the US gross petroleum imports by country of origin as a percentage of total oil consumed. It is interesting to notice that while OPEC countries (green-colored countries in the chart) continue to respond for the supply of roughly 30% of the US oil consumption, non-OPEC countries (blue-colored ones) are now responsible for the supply of roughly 32% of the oil consumed in the US. This is a sign that the USA is actually moving away from the extreme oil dependence to OPEC countries, an issue raised by APS in the late 90s. This clear move from the dependence from OPEC-sourced oil has led to a major shift towards long-term, reliable neighbor countries, with Canada now being US largest supplier of oil. Mexico, the UK, and Brazil, also stable nations with strong economic interests with the USA, have increased immensely its participation in the supply of oil to the USA since the 1980's, as presented in Exhibit 1.

Climate Change

Data collected by various international agencies has showed that climate change is a global problem that has been increasingly worsening the quality of life on Earth. There is scientific consensus of global warming, exemplified by Exhibit 2, which presents a chart with temperature measurements showing that, regardless of geographic location, temperatures are rising. Nevertheless, potential consequences are much debated, both publicly and politically.

Effects attributed to global warming include physical, ecological, social, and economic changes. While physical and ecological consequences range from extreme weather changes and glacier retreat to ocean acidification and the rise of sea level, social issues include impact on the food supply (due to the elevated concentration of CO_2 in the atmosphere, higher temperatures, altered precipitation, and the increased frequency of extreme events) and on health (changes in water, air and food quality, as well as changes in weather patterns). Scholars have argued that political risks and conflicts can arise due to heightened competition over natural resources of increased scarcity[6,7].

Most of the green sources of energy explored around the world in the time being could, however, intensify political risks and conflicts. There is inherent interest in specific windy or sunny locations, as they can yield higher energy productivity for renewable energy sources. However, these locations are also optimal for food production or the settlement of populations. Therefore, it is also consensus, to some extent, that there is only one possible solution to this imminent set of problems, which is the reduction in the CO_2 emissions from human-related activities.

Rising Cost and Consumption of Energy

Exhibit 3 presents both nominal and real (CPI-adjusted) crude oil prices over the last forty years. Current real prices of crude oil are only comparable to the ones observed during the Iranian Revolution from the late-70s to the early-80s. While it is well known that supply and demand alone are not the only predictors of oil prices, the cartelization of the industry prevents countries from completely protecting themselves against unexpected price peaks, despite the short- and medium-term palliative solution of hedging through financial derivatives.

While the rising cost of energy is an unpredictable variable, it is one that strongly influences the economic growth of a country. This is because a country's GDP is directly correlated to its energy consumption (see Exhibit 4). As a country's economic output grows, the

6. Wilbanks, T.J. *et al.* "Industry, settlement and society." Parry, 2007: 357-390.
7. Zhang, D.; Brecke, P.; Lee, H.; He, Y.; Zhang, J. (2007) "Global climate change, war, and population decline in recent human history". Proceedings of the National Academy of Sciences of the United States of America 104 (49): 19214-19219. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2148270/?tool=pmcentrez.

country will necessarily require greater energy consumption. To illustrate this point, linear regressions between these variables were run from the early 1980's through 2007. For example, the regression of the last year, for which data were fully available (2007), is displayed in Exhibit 4. The correlation between total GDP (in PPP terms) and total primary energy consumption for that year is roughly 0.95.

It is important to highlight the fact that the presence of the USA within the dataset greatly influences the regression's fit curve, its statistical significance, and the resulting predicted curve. This paper attempts to understand the USA's effect in the global context, and how the US's energy patterns impact the energy consumption trend of emerging markets. By including the US in the regression, the fact that the USA plays a very important role in the current analysis is acknowledged, as its presence greatly influences future outcomes for emerging economies. The US has been emerging economies' major role-model of economic success and growth, and therefore might be a good representation of what lies ahead for them if energy consumption patterns do not change.

As shown in Exhibit 4, the direct correlation between a country's economic growth and its consumption of energy is highly statistically significant. However, the ability of a country to increase its primary energy production (and consequently its consumption) depends on the cost of adding capacity to its portfolio of power generation plants. If the fuel of choice is not readily available, a country's dependence on the international, cartelized costs of coal, oil, and gas might lead to road blocks in a country's development efforts. One of the fundamental issues for a country willing to grow economically is its capacity to generate more power, and therefore, the internationally observed cost of energy-related commodities plays a major role in determining the likelihood of a country's success in achieving lasting GDP growth.

Finally, with the rapid rise of emerging economies, and the even faster growth of the worldwide middle class, organic energy consumption growth rate is expected to increase, thus greatly impacting power generation capacity requirements. Studies show that there are roughly two billion people who are not yet connected to electric power grids[8]. As countries grow economically, it is expected that the electric infrastructure will have more capillarity with deeper penetration. This imminent increase in the penetration of electricity among lower classes in developing nations will boost demand for electricity in the coming years to an unprecedented level and require substantial improvement in the quality and quantity of power output all over the world.

Vicious Cycle of the Current Energy Generation Model

There is a direct correlation between GDP growth and growth in power consumption, as detailed above. Therefore, the quick rise of emerging economies has been seen as a real threat in terms of emissions of pollutants and its inherent consequences as several of these economies rely on fossil fuels. Issues such as the unavoidable exhaustion of natural reserves, the implicit rising cost of power-related commodities such as oil and coal, and energy security needs have only aggravated with the enormous increase in global power consumption as emerging economies have grown in recent decades. These factors have combined to form a vicious cycle in the current energy generation model, i.e., more energy produced leads to more negative environmental impact and more negative environmental impact leads to higher global energy requirements, because there is a resulting need to try to address the negative impact directly through corrective or adaptive expenditures to more extreme weather conditions.

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8. Mankins, J.C., “A Fresh Look at Space Solar Power: New Architectures, Concepts and Technologies”, 38th International Astronautical Federation, 1997 (hereafter cited as *Mankins, Fresh Look*).

Planet Earth is the only viable habitat for human beings (thus far), so any impact on the surface of the earth or its atmosphere can be considered an endogenous problem – endogenous to our habitat, our environment - with potential impact to our survivability. There is only one way to reduce the worsening conditions that arise from the increase in the generation and consumption of energy (however it is produced), which is to somehow manage to transform this inherently endogenous issue into an exogenous one. This is one of the main goals of a Solar Power Satellite, i.e., to generate power in such a way that it does not depend on endogenous variables (e.g., availability of fossil fuels, wind, sunlight, and water), therefore without causing any potential harm to our habitat, the Earth.

The next subsection describes some of the best known options available for energy generation and briefly discusses the advantages and drawbacks of each.

Endogeneity of Current Energy Generation Options

Nuclear Power

Nuclear power plants are a great solution for the CO_2 issue. They are able to emit up to 98% less CO_2 per KWh of electricity generated than coal power plants[9, 10]. Nevertheless, nuclear power plants are probably the source of energy that faces the greatest resistance from the society. From the bad image caused by the accident of Chernobyl in 1986 (and the related popular manifestations such as the NIMBY – *Not in my backyard* – movement) to today's improved security measures, enhanced technological systems and plant's efficiency, a lot has changed, except for the population acceptance. In 1987, only a year after the Chernobyl accident, Italy

9. Spadaro, Joseph V. et al (2000) "Greenhouse Gas Emissions of Electricity Generation Chains – Assessing the Difference". International Atomic Energy Agency. http://www.iaea.org/Publications/Magazines/Bulletin/Bull422/article4.pdf .
10. "Greenhouse Gas Emissions from Power Generation." World Nuclear Association, accessed October 3, 2010, http://www.world-nuclear.org/why/greenhouse_gas_from_generation.html (hereafter cited as *WNA, Emissions*).

held a referendum, in which the Italians decided to phase out Italy's power plants. It took almost two decades for Italy to, despite public criticism, pursue the development of a new generation of nuclear power plants. The March 11th 2011 earthquake off the coast of Japan and the damage sustained by the Fukushima nuclear reactors has more recently contributed to the public fears. At this writing there was much still uncertain, but it was clear that one of the consequences of the Japanese earthquake and its resulting nuclear accident would be a complete reassessment of nuclear power.

According to public acceptance surveys carried out by the International Atomic Energy Agency (IAEA), while 70% of the UK population strongly opposed the development of nuclear power plants within the UK in 1987 (short after the Chernobyl accident), in 2009 only 35% were opposed to nuclear power, whereas roughly 50% were in favor of nuclear power in 2009. An even stronger trend was noticed in the USA, with roughly 20% of the American population opposing power plants in 2009 against 65% in favor of its careful development[11].

Although recent surveys have indicated an increase in public acceptance for nuclear power plants, the recent earthquake in Japan, and its subsequent tsunami, has cooled public acceptance[12], by showing the world how powerless mankind is when it comes to environmental disasters. With the worsening of environmental conditions and the increased likelihood of extreme weather events, nuclear power plants might be seen as major potential threats, ready to cause catastrophic impacts where they are located and surroundings.

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11. "Dealing with Public Acceptance for Nuclear Power." International Atomic Energy Agency, last modified September 23, 2008, http://www.iea.org/work/2008/bangkok/toth_acceptance.pdf.
12. "Japan's Disaster May Cool U.S. Acceptance of Nuclear Power." LiveScience Website, accessed March 27, 2011, http://www.livescience.com/13240-japan-disaster-sway-perception-nuclear-power.html.

Another major issue on nuclear power plants is the large generation of nuclear waste, whose decay process into acceptable radioactive levels takes hundreds of years. Throughout these years, a safe, enclosed environment is needed. These enclosed environments might be targets for terrorism, might suffer from extreme weather conditions, or from cataclysms, and any leakage could have catastrophic proportions.

Coal Power Plants

Due to its ready availability and the relatively low complexity of its plants, coal is still seen as an easy fix to increasingly growing energy needs, such as in the recent industrialization process carried out by China. For example, in 2010 China added a new coal-fired plant every 10 days[13]. This incredible growth in the Chinese electricity generation capacity mainly through coal-fired power plants has led China to take the lead as the world's greatest emitter of greenhouse gases.

Coal is still the first solution to the increasing power needs of growing economies primarily due to its low cost. The direct correlation between economic growth and a country's ability to produce more energy leads emerging economies to look for solutions that are economically viable in the short-run to support and maintain their economic growth. Exhibit 5 presents a range of CO_2 emissions per KWh of electricity generated for each type of power plant presented in this chapter. Although technologies lowering the CO_2 emissions of coal power plants have been developed, coal is still by far the energy source that causes the greatest environmental impact in terms of greenhouse emissions, i.e., coal is causing the greatest endogenous impact of all energy sources listed in this paper. Besides the large emissions of CO_2 per KWh of electricity generated, coal plants also face resistance in the coal producing locations.

13. "Pollution from Chinese Coal Casts a Global Shadow." The website of The New York Times, last modified June 11, 2006, http://www.nytimes.com/2006/06/11/business/worldbusiness/11chinacoal.html.

Local populations have been fighting against the environmental impact of coal mining, from human worker conditions to mountaintop removal to the destruction of vegetation and regional landscapes.

Hydroelectric Plants

Hydropower is the most widely used form of renewable energy. In 2008, it accounted for 85% of electricity from renewable sources[14]. One of the biggest advantages of hydropower is its virtual independence from fuel-related commodity cost increases, allowing a country to reach independence in terms of imported energy-related commodities, such as oil, coal, or natural gas. If well maintained, hydroelectric power plants also enjoy a long life cycle (that can range anywhere from fifty to a hundred years of operating life). CO_2 emissions levels are also very low, and are originated almost entirely from lifecycle causes (i.e. construction and maintenance rather than from operations, unlike coal and gas plants).

Although hydropower enjoys a very high level of acceptance among populations in most parts of the world, it presents some major drawbacks, such as environmental impact, loss of land, population relocation needs, and the constant risk of a catastrophe in case of a major failure in dam structure. The most common cause of mobilization from non-governmental environmental organizations is the environmental impact and the loss of productive lands that the construction of major hydroelectric power plants cause. A hydropower plant usually requires a large reservoir. This requires a large area to be inundated, virtually always destroying biologically rich and productive lowlands. The second biggest concern is the need to dislocate people from their original habitats. It is estimated that 40-80 million people have been physically displaced as a

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14. "Renewables 2010 – Global Status Report." Renewable Energy Policy Network for the 21st Century, accessed September 19, 2010, http://www.ren21.net/Portals/97/documents/GSR/REN21_GSR_2010_full_revised%20Sept2010.pdf (hereafter cited as *Renewables 2010*).

direct result of dam constructions worldwide[15]. Finally, the collapse of a dam can cause very large areas to be submerged, impacting local populations. Furthermore, dams have been target of sabotage, terrorism, and war efforts, such as Operation Chastise in World War II, carried out by the British Air Force to destroy German Dams that provided not only electricity to major industrial towns, but also potable water to the neighboring populations[16].

Solar Power

One of the main advantages of solar power is that its adopter becomes less dependent on fossil fuel supplies, its cartelized players, and resulting uncertain costs. One additional advantage of solar power is the use of existing unused real estate as its infrastructure, especially in single-family houses, where it is usually installed on rooftops, eliminating the problem of finding the required space for solar panels. It is also considered a very clean technology, as it produces virtually no CO_2 while generating electricity (although it does have larger emissions than wind, hydro, and nuclear throughout its life) and no noise. Its economical viability is also a crucial decision factor for adopters, who usually see their initial investment breakeven in a couple of years.

Solar panels also have a major drawback – their dependence on local weather conditions. Solar power efficiency is dependent on the availability of sunshine and seasonal factors (winters have fewer daily hours available for energy production than summers). Weather predictability helps this system be more efficient. Weather is more predictable to the extent that less extreme weather patterns occur. Lower greenhouse emissions help extreme weather patterns be reduced

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15. "The World Commission on Dams Framework – A Brief Introduction." International rivers organization, last modified February 29, 2008, http://www.internationalrivers.org/en/way-forward/world-commission-dams/world-commission-dams-framework-brief-introduction.
16. "Operation Chastise." The Dambusters Website, accessed October 4, 2010, http://www.thedambusters.org.uk/chastise_index.html.

and, in order for this goal to be reached, renewable sources of energy are needed. In other words, solar panels depend upon the local environmental conditions where they are installed – although they are mostly adopted as a means to reduce the environmental impact that the generation of electricity creates. This can be viewed as a circular reference, i.e., the variable you try to determine is dependent upon itself.

Several variables influence the efficiency of solar power, such as pollution, the assumption that sunlight will always be available in the same location (i.e. nothing can block the sunlight that is supposed to be absorbed by the solar panels to generate electricity), and the degradation of solar panels over its life cycle (on average 2 to 3% per year[17]). This means that solar panels are expected to halve its electricity generating capacity in anywhere from 24 to 36 years, which has significant impact to the investor, as additional sources will be needed to cover these losses in capacity to produce electricity, while consumption will likely continue to grow over time. Also, this means that reinvestments are needed in order for a certain location to continue producing the same amount of electricity.

Finally, a major issue faced by big investors concerns real estate availability where electricity is most needed. Although several stakeholders, such as governments, societies, industrial firms, etc., have quickly accepted the concept of solar farms, the availability of reasonably low-cost real estate is a major hurdle for a solar farm to be economically and financially viable. And this issue, already mentioned above, faces skepticism from specialists and especially from non-governmental organizations focusing on fighting hunger and undernourishment. These organizations believe that the use of large areas of land that receive a

17. "Photovoltaic Panels Efficiency Degradation Factors." Renewable Energy Sources Website, accessed October 3, 2010, http://www.renewable-energy-sources.com/2009/07/30/pv-panels-efficiency-degradation-factors/.

great influx of sunlight could better be used for agricultural production, so as to help reduce the large number of undernourished people. This is especially relevant in tropical areas, in which poverty levels are higher, as exemplified by the DESERTEC project, which intends to produce a vast amount of electricity in North Africa to cope with the increase in the European demand[18]. Although the North-African nations targeted for the DESERTEC project have most of their territories covered by the Sahara desert, with the proper availability of energy, farms could be established, as water could be pumped inland for agricultural purposes or for the needed improvement of quality of life in that area of the globe.

Wind Power

Wind and solar power share two similar advantages – the capacity to generate electricity in remote areas that are not covered by national electricity grids, and the fact that these sources of energy are readily available in nature at no cost. Also, because it takes up only a relatively small plot of land, wind power has quickly spread out, especially across Europe. Besides its size and generation capability, wind energy has seen an immense growth fueled by government tax rebates and other incentives. This is one of the greatest incentives for investors to develop and install this technology – in general, it takes an average of 10 years for an investor to break even its initial investment in the windmills, as long as governments maintain the tax incentives and keep on protecting the indigenous players as they have been doing thus far.

Although the wind power industry has seen 112% growth worldwide from 2006 to 2010, and is expected to grow roughly 800% through 2030[19], it faces some skepticism from critics and specialists in the energy industry. First, the ten-year break even period depends on the local wind

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18. "DESERTEC Foundation." The Website of the Desertec Project, accessed September 19, 2010, http://www.desertec.org.
19. "Global Cumulative Wind Power Capacity." Global Wind Energy Council, accessed October 4, 2010, http://www.gwec.net/fileadmin/images/Publications/Global_cumulative_wind_power_capacity.jpg.

speeds averaging ten miles per hour for long periods of time, besides subsidies. Locations where the wind speed reaches this average are usually places where there is a high likelihood of strong storms – in which case a windmill could work as a lightning rod, attracting lightning due to its height. Once windmills are struck by lightning, both their structure and their capability of generating power are subject to damage. Therefore, the expected time to breakeven can actually vary widely, and maintenance costs can pose major threats to its economic viability, even with governmental tax benefits. Another frequent source of complaints from people who live nearby windmills is the noise, which is inversely proportional to the wind speed – i.e. the lower the speed, the noisier the windmill. This invariably causes an even worse perception on neighboring communities. In addition to these common complaints faced by the wind turbine industry, wind turbines are also perceived as bird-killer agents[20] that interrupt birds' migratory paths by being located exactly in the optimal wind paths used by birds in their migratory routes. Finally, windmill technology can also be seen as having a major logical drawback in its functioning, as it depends on the environmental conditions of certain locations, as described for solar energy technology.

Historical Background of Solar Power Satellites (SPS)

The previous section shed light on the currently most popular and widely utilized energy sources. It becomes clear from the descriptions and the pros and cons listed for each energy source, that each one of them either causes further environmental impact (coal, hydro, nuclear), or depends upon the environment to operate appropriately. In other words, they are all endogenously intertwined, either aggravating environmental conditions or depending upon them.

20. WSJ, Windmills.

Since none of the options available present an optimal solution for the energy issues currently faced by most nations around the world, it becomes crucial that new technologies emerge. The objective of this section is to explain the historical and strategic reasons that caused the idea of Solar Power Satellites systems to surface, and how this purely exogenous power source can help reshape energy generation. This section also briefly comments on current studies being carried out in this field, and identifies some critical developmental breakthroughs that are expected to happen in the years ahead.

The Cold War, the Space Exploration Programs, and the Oil Crisis in the 70s

The unique possibility of generating large amounts of energy in space to be beamed by satellites for terrestrial applications was first suggested during the Cold War. At that time, both the Soviet Union and the USA were engaged in a fierce competition for space exploration. Major technological breakthroughs were achieved in the late sixties, which enabled the Soviet Union to send the first man to space, and the USA to land the first man on the surface of the moon. The availability of advanced space and satellite technologies enabled scientists to envision concepts of power generation in space to be beamed down to earth for various terrestrial applications. The energy shortages of 1973 revitalized conceptual discussions that had begun in the late sixties – the USA needed a higher level of energy security to drive economic growth. In early 1976, the Department of Energy (DOE) and NASA initiated an SPS concept development and evaluation program[21].

Following the joint study conducted by the DOE and NASA from 1976 through 1980, a preliminary concept was created, and several recommendations were made, with suggestions regarding next steps, so that the concept could be refined and further developed. The preliminary

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21. NSS, SPS.

concept resembled that which was suggested by Dr. Peter E. Glaser in 1968[22]. It was constituted of a primary electrical source that involved generating electrical power from solar energy in a geosynchronous orbit, transmitting the power to earth via focused microwave beams, and collecting and converting the microwave beams into useful electricity on the earth's surface through receiving antennas (rectennas). Additional modular features were considered and analyzed, and although the document contained a vast amount of detailed information, the technological breakthroughs required for such a system to operate optimally had not yet been developed enough. Assumptions made in that report estimated that the concept could become a reality by the year 2000. The concept was therefore then stored for later use, once additional breakthroughs allowed it to become a technologically feasible energy source.

9/11 as an Opportunity to Move away from the Oil/Coal Hold-up Position

Strategically speaking, there could have been no better moment to further develop such a complex energy generating source than the post-9/11 period. Counting with extremely high public support and the full commitment of tax-payers and industrialists, this point in time could have marked the beginning of a new era of space exploration to take advantage of the virtually infinite amount of energy which is independent from seasonal factors and local weather conditions. The intensity of radiation intercepted in the near-Earth space is about 1.35KW/m^2, on average roughly 580% higher than the radiation that strikes the earth's surface[23]. Exhibit 6 shows the seasonality of solar radiation that strikes the earth due to the inherent solstice-equinox positioning of the earth along its orbit around the sun.

22. Dr. Glaser, Peter E., "Power from the Sun – Its Future". Science, Vol. 162, November 22, 1968, pp 857-861.
23. Dr. Lior, Noam. "Power from space". Energy conversion and management 42, 2001 (hereafter cited as *NL, Power from Space*).

With the economic downturn that followed the terrorist attacks to the World Trade Center, oil prices plummeted. Exhibit 7 presents a set of historical data on oil prices from 1970 through 2009 (in 2008 USD). Although public support and investments could have been directed towards the development of SPS so as to reduce the U.S. dependence on foreign energy-related commodities (especially from the highly cartelized OPEC countries), the lower prices of fossil fuel commodities due to much reduced demand caused most decision-makers (including SPS stakeholders) to maintain reliance on oil.

While there has not been significant focus to further develop SPS, even with investments that are several orders of magnitude lower than the investments directed towards other renewable energy sources, important developments took place in the 1990's. That point in time marked a series of studies (by NASA, Boeing, and other government-sponsored agencies), which started redeeming the popularity of the concept of Solar Power Satellites.

Funds have not been made available to develop space-based solar power concepts. In the last three decades, NASA and the Department of Energy have collectively spent $80M on SPS studies, whereas nuclear fusion developments received $21B of investments in the same timeframe.[24] While first studies pointed out to financial and economic factors as the major difficulties in the development of SPS, these early studies relied on the simple extrapolation of oil prices, which pointed out to a slightly positive-sloped curve, indicating a small increment in prices over time. In the decade since 9/11, this scenario has changed considerably. Oil prices skyrocketed from $15/barrel to over $145/ barrel[25] in less than a decade. SPS systems seem like

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24. "Space-Based Solar Power as an Opportunity for Strategic Security". National Security Space Office, last modified October 10, 2007, http://www.nss.org/settlement/ssp/library/nsso.htm (hereafter cited as *NSSO, SBSP*).
25. Price at the closing of the trading session on the New York Mercantile Exchange on July 3rd 2008.

a much more attractive proposition from an economic standpoint in early 2011 than in 2001, as its competing energy sources have seen a ten-fold rise in costs.

Current Studies

A detailed study conducted in 2007 by the National Security Space Office (NSSO) on the technical, strategic, economic and financial feasibility of Space-Based Solar Power reached several conclusions. First, that the strategic opportunity offered by SPS could significantly advance US and partner security, capability, and freedom of action, which in turn could further draw attention from both public and private sector investments. Second, although some technical issues remain partially unanswered, such an energy source is more executable now than ever before due to recent technological advancements. Third, it suggests that a proof-of-concept prototype could further increase chances of private investments as well as international cooperation, so as to mitigate some of the technological risks raised so far.

Following these conclusions, several new studies arose, and a number of private firms began to heavily invest time, expertise, and resources into this technology. The high visibility caused by recent discussions and developments in this area spurred interest from U.S. state governments, with the goal of minimizing dependence on oil, coal, and gas, while mitigating risks of further environmental impact. For example, the government of California has signed a contract for procurement of Renewable Energy Resources with Solaren Corporation, which will provide the State of California with power generated in Space by SPS and beamed to earth for terrestrial applications by 2016[26]. This agreement is the first of its kind, and can pave the way to a new wave of investments from the private sector in this field of technology, providing the U.S.

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26. "Contract for Procurement of Renewable Energy Resources Resulting from PG&E's Power Purchase Agreement with Solaren Corporation." Public Utilities Commission of the State of California, December 3, 2009, http://docs.cpuc.ca.gov/PUBLISHED/FINAL_RESOLUTION/110808.htm (hereafter cited as *PG&E PPA*).

with a head-start in this cutting-edge new era of space exploration, with sustainable and renewable energy-generating objectives.

Other private investments can be found in different countries, from Japan[27] to the United Kingdom[28], and studies have been converging in terms of technology choices, and even in terms of economic and financial viability. These developments signal that the 40-year old concept of Space-Based Solar Power can become reality in the current decade if, among other pre-requisites, countries align efforts, if appropriate policies are put in place, and if similar incentives as the ones given to nuclear fusion, wind, and solar power, are provided.

Advantages & Drawbacks of SPS

While most issues raised as potential challenges for the development of SPS are directly related to costs (development, production, launching, and maintenance costs, to name a few), other drawbacks are worth mentioning. For example, power collected by solar arrays needs to be electromagnetically beamed to earth for terrestrial use. However, this technology has not been extensively tested yet (at least not in this order of magnitude), and could be a potential hurdle to the development of SPS. Also, since the SPS is expected to orbit around the earth, it faces potential damages by meteorites and cosmic dust. Finally, international agreements have to be made on space use and power distribution.

Although some risks mentioned above deserve careful and thorough assessment, so as to mitigate these potential drawbacks of Space-Based Solar Power systems, SPS systems present a

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27. "Solarbird Space Systems." The Mitsubishi Electric Website, accessed October 4, 2010, http://global.mitsubishielectric.com/bu/space/rd/solarbird/index.html.
28. "Energy market drivers behind Space Solar Power." The Powersat Corporation Website, accessed October 4, 2010, http://www.powersat.com/.

wide variety of advantages over any other energy source. First, the energy generation potential is enormous, in that a single kilometer-wide band of geosynchronous earth orbit experiences as much solar flux in one year as the amount of energy contained within all known remaining oil reserves on Earth today[29] – and it could do so without emitting greenhouse gases, or generating any other environmental, social, or political side-effects, i.e., in a purely exogenous way, unlike any other currently existing energy source. Second, SPS can generate electricity around the clock, and its performance does not depend on season, weather conditions, or atmospheric pollution, unlike solar and wind power sources. Third, with the absence of gravitational force, SPS's structure can be much lighter than any other infrastructure on energy sources on the earth, resulting in much less complex structures. Fourth, there are several reasons to believe that a SPS can last much longer than any other power plant on earth, because of the absence of oxidizing agents, rain, dust, hail, and vandalism[30]. Fifth, accidents would not cause any harm to people or nature, unlike those of hydro or nuclear power plants, to name a few. Sixth, due to the inherent flexibility of the operation and deployment of the SPS systems, power could be beamed directly to isolated areas that have been affected either by natural catastrophes or by armed conflicts, unlike any other existing power generating method. Finally, energy can easily be beamed to the direct consumer, as needed, which enables this system to operate in a unique manner: capturing the entire upside of the energy where it is needed in peak times, and selling electricity at the peak prices on the spot market in different countries, according to local demand and seasonality issues.

29. NSSO, SBSP.
30. NL, Power from Space.

THE TECHNOLOGY OF POWER GENERATION IN SPACE

The previous sections of this paper have set the foundations to understand why a reliable, secure, expandable, non-polluting, truly exogenous source of energy is a global necessity. Space-Based Solar Power is very well positioned to capture this opportunity and become the leading source of electricity around the world in the future. This section sheds light on the technological concept of Solar Power Satellites which has very simple basic idea: to place very large solar arrays into earth orbit, collect large amounts of electrical energy, electromagnetically beam this energy to Earth, and receive it on the surface for terrestrial uses[31].

Architectures

Two SPS architectures are described in this paper: the Sun Tower and the Solar Disc. NASA and Boeing have studied extensively both concepts in the past decades, and published a vast amount of papers on these emerging technologies. The descriptions are largely based on Mankins' "Fresh Look at Space Solar Power" paper published in the late 1990s, and further analyzed and detailed in the NSSO study of 2007.

Sun Tower

The SunTower concept involves four major components: the backbone, the solar power arrays, the transmitting phased array, and other miscellaneous elements. A gravity gradient tether-backbone is deployed as part of the tension-stabilized structure design. The backbone is 15 km long and connected to 340 pairs of solar collectors and a circular transmission array facing earth. Each solar collector is 50-60 meters in diagonal with 1MW net electrical output. The transmitter is 200-300 meters in diagonal with a transmitting frequency of 5.8GHz. Electronic

31. NSSO, SBSP.

beam steering instead of mechanical pointing is used to guide the radio frequency (RF) beam. The system would initially be deployed in low earth orbit (LEO) and later be migrated to a higher Earth orbit, either middle earth orbit (MEO), or geostationary earth orbit (GEO). It would be located in a sun-synchronous orbit, so a solar pointing system would not be required. Exhibit 8 depicts the Sun Tower SPS concept, as envisioned by Mankins, and Exhibit 9 presents an artistic rendering of the Sun Tower system.

Due to the extensive modularity of the design, relatively small individual systems can be built and tested with existing facilities, and the manufacturing of the actual SunTower can be done in a mass production style, benefiting from the economies of scale provided by the large amount of solar panels or other components needed. Heavy Lift Launch Vehicles (HLLV) transporting the four components separately are suggested as a means to minimize the costs associated with launching the SunTower into space. However, combining and stabilizing the four parts in space would require either assembly by personnel or equipment, which could imply high costs, or very elaborate kinetically deployed mechanical systems, which can be exceptionally complex and involve large risks[32].

The general design of the ground receiver is a rectifying antenna (rectenna). It would be a 4km diameter site with direct electrical feed into a commercial power utilities interface (Exhibit 10 presents an image of what a rectenna would look like). Exhibit 11 shows a potential location of a rectenna, on the suburbs of a major city. Once the beam is intercepted by the rectenna, it is converted back into electricity. The electricity is then rectified to alternating current (AC), and

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32. Mankins, J.C. “A technical overview of the ‘SunTower’ solar power satellite concept”. Acta Astronautica 50 (2002): 369-377.

fed into the power grid[33]. Although rectennas require a large piece of land in which to be installed, it is important to highlight that the piece of land utilized for the rectenna does not necessarily need to go unused. Since the intercepting array absorbs the microwaves, but allows sunlight and rainfall through, the land could be used for farming or ranching without causing any harm to plants or people underneath. Alternatively, the rectenna could be built as a vast set of greenhouses[34], in which case the rectenna would serve multiple purposes: intercepting and converting the power beamed from space, and enabling greenhouses to be installed underneath, creating a potentially optimal environment for food to be grown. This is an important advantage of the SPS system versus any other green energy source. As previously mentioned in this paper, other sources of green energy bring with them inherent endogenous issues, e.g., the use of a potentially productive piece of land for the production of energy to be consumed by richer countries, in what can be seen as cannibalization of land, where a silent auction takes place backstage between hungry, impoverished countries, and richer countries in need of additional sources of energy. Developed nations, with aligned needs and similar goals could outbid local agricultural or real-estate players in an unethical, but potentially realistic scenario of dispute for specific pieces of land that are especially suitable for the installation of solar, wind, or hydropower plants. This effect of globalization is rather negative for impoverished nations, where the main focus is on survivability rather than on protecting their assets. In other words, sometimes economic incentives are misaligned with environmental goals.

33. "The Space Settlement Art Gallery", accessed September 19, 2010, http://space.mike-combs.com/gallery.htm (hereafter cited as *SSAG*).
34. SSAG.

Solar Disc

The Solar Disc is a single, rotationally stabilized, spirally constructed, GEO-based system using differentially spinning elements. A solar disk would have an approximately 3-6 km diameter. Power is collected from groups of solar panels connected to provide the voltage required. The center of the disk integrates the power collected and conveyed to the transmitter array. The array is about 1km in diameter and approximately 1.5-3.0 meters in thickness. A single transmitting element is projected to be an hexagonal surface about 5 cm in diameter. One Solar Disc system is estimated to generate power anywhere within a 1-12 GW range. The rotation ensures that the transmitter array is continuously pointing to earth and the solar panels are continuously pointing to the sun. Exhibit 12 depicts the Solar Disc SPS concept, as envisioned by Mankins, and Exhibit 13 presents an artistic rendering of the Solar Disc system. A unique and cost-effective LEO-to-GEO in-space transportation system is critical to the technical viability of this system. Just as the Sun Tower system, the Solar Disc also has a highly modularized design, which minimizes potential transportation and maintenance issues.

The ground receiver is a 5-6+ km site and connects directly to the local utilities' interface. This ground receiver would be very similar to the one needed for the Sun Tower. The characteristics of the receiving antenna would also be similar, and the benefits of this rectenna would be identical to the ones presented for the Sun Tower. Another important similarity shared by both systems is that multiple ground sites can be served from one SPS system. The benefit of having several ground stations served from one SPS system is that the SPS can beam its produced energy to spots that lack energy the most or that present a more urgent need for electricity, either due to damaged existing power sources, or due to environmental issues, or as a means to spur growth of a certain area or industry that does not have electricity infrastructure in place. This would be extremely beneficial from an economic standpoint because it would make it possible for the operator of the SPS to beam the power generated in space to places with the highest willingness-to-pay, therefore capturing the peak of the surplus curves in each location, and boosting its revenues from these places.

Space Satellite Positioning

Possible deployment locations for SPS systems include Low-Earth Orbit (LEO), Middle-Earth Orbit (MEO), Geostationary Earth Orbit (GEO), as presented by Exhibit 17, and the moon. The following sections will discuss the advantages and weaknesses of each option.

Low Earth Orbit (LEO)

A Low Earth Orbit is defined as an orbit between 160 and 2,000 km above the surface of the earth. If deployed within LEO range, it would be on a specific sun-synchronous orbit, in which the satellite passes all latitudes at the same time as the sun every day. LEO is the closest to earth among all options, and has been identified as the lowest *cost to first power*, i.e., the lowest total cost that would enable a space-based solar power source to become operational. The short distance minimizes the complexity of power transmission, the required size and weight of the transmitting antenna, and the energy cost of earth-to-orbit transportation. LEO could also conceivably become a primary assembly and transfer location for higher orbits.

However, satellites in LEO would spend much time in the Earth's shadow and therefore have significantly lower productivity. One satellite could serve an individual receiving site on the Earth for only a few minutes. As a result, it would require sophisticated beam steering to cover more area on the Earth and a large number of ground stations to maximize productivity. In addition, without an effective capability to de-orbit space debris, a LEO-based object of such large size and surface area would be exposed to the large amount of artificial debris and faced with high damage risks.

Middle Earth Orbit (MEO)

Middle Earth Orbit is defined as orbits that lie between 2,000 and 36,000 km above the surface of the earth. The so-called Low MEO orbit is at the altitude of 6,000 km and High MEO is at 12,000 km. The longer distance substantially reduces the required beam steering. Much less time is spent in the Earth's shadow as the LEO positioning and therefore the productivity is higher. Continuous power supply can be achieved by a constellation of satellites, either on the same orbit or multiple orbits.

However, the longer distance would also require larger apertures and higher systems weights. The transportation cost from earth to orbit would be much higher. There is also exposure to radiation, which may result in equipment degradation. Power transmission would have to cross many other satellite orbits to reach earth, and the potential impact of interference also needs to be considered.

Geostationary Earth Orbit (GEO)

The Geostationary Earth Orbit is at the altitude of 36,000 km and has a revolution of exactly one day. The orbital period of a GEO-based satellite corresponds to the speed of earth's rotation, which means that the satellite would always be above the same location on earth. This characteristic allows very little beam steering and continuous power supply from a single satellite to one receiving station on earth. Due to the axial tilt of the earth with respect to the sun, the satellite spends less than 1% of the total time in the Earth's shadow, which optimizes productivity. Other benefits of GEO include less environmental impact due to no beam slewing, less debris on the orbit, more room available in GEO orbit and more Earth surface visibility.

On the other hand, because GEO is the highest orbit, satellites would have to be larger and use more power to compensate for the distance from the Earth. The beam would need to go through all other orbits and, similarly to MEO, potential impact possibility must be considered. Transportation costs would also skyrocket. In addition, the GEO orbit is already widely used for other satellites such as communications and television satellites, as it allows a satellite to be in continuous communication to a certain point on the surface of the earth. That imposes more complications when deploying the large SPS system on the orbit.

Surface of the Moon

Another option considered is to construct power collection and beaming equipment on the moon. Since raw materials from the moon can be utilized, the weight to be transported from Earth to space would be minimized and so would the associated costs. However, due to the orbital plane of the moon, all locations on the moon experience a 14-day lunar night. As a result, power collectors must be constructed on both the east and west side of the moon to provide constant power. Power from the moon must be beamed a long distance with high precision steering since the moon is not geostationary. It would also require reflectors or re-transmitters in Earth's orbit, or a global distribution grid to enable continuous power on different locations on earth. The initial launching and installation costs would be extremely high, although it is possible that the infrastructure on the moon could be used for later space exploration purposes as well.

This option is recognized as the least viable option due to the additional technical constraints – from the need to install different sets of power collectors on different sides of the moon, to the need to install reflectors or re-transmitters. Furthermore, a global distribution system integrating power grids worldwide seems of extremely difficult execution.

Energy-Capture Methods

Photovoltaic

Photovoltaic (PV) cells enable the conversion of solar radiation into direct current electricity. Photovoltaic materials absorb photons upon exposure to light, and release electrons. The free electrons move through the cell and fill in orifices, creating direct current electricity. One single PV cell only produces up to 2 watts of power. As a result, a number of PV cells must be electrically and physically connected on a support structure to form a PV solar module, which can provide enough power output in various levels for different applications. Multiple modules wired together form a PV solar array. The overall PV solar array efficiencies range from 6% to 25%. Experimental high efficiency solar cells have also been developed, with an efficiency of over 40%[35]. Solar concentrators can be made at low cost and could be used to augment the PV cell output. Crystalline materials have a uniform molecular structure and therefore have higher efficiency compared to non-crystalline materials. Among crystalline materials, Silicon and Gallium Arsenide (GaAs) are the current prime candidate materials for PV cells.

Silicon has an electricity output to weight ratio of 30 W/kg[36] (this is a typical measurement of efficiency for these types of materials, representing the energy output per unit of mass of these materials employed). There are two types of crystalline silicon, single-crystal silicon and polycrystalline silicon. A single-crystal solid is a material with continuous crystal lattice over the entire sample with no grain boundaries. The absence of the defects from grain boundaries gives single-crystal materials special characteristics. Single-crystal silicon has a high conversion efficiency of 15-20%, and it is very reliable in energy output and outdoor

35. "World Record: 41.1% efficiency reached for multi-junction solar cells at Fraunhofer ISE." Franhofer Institut, last modified January 14, 2009, http://www.ise.fraunhofer.de/press-and-media/press-releases/press-releases-2009/world-record-41.1-efficiency-reached-for-multi-junction-solar-cells-at-fraunhofer-ise.
36. NL, Power from Space.

environments[37]. However, single-crystalline silicon incurs high manufacturing costs, mainly due to silicon loss in the wafering process. The opposite of single-crystal is an amorphous structure. In between the two extremes is polycrystalline, a material that is composed of many crystallites of varying size and orientation. The different orientation can be either random or directed. Compared to single-crystal silicon, polycrystalline silicon is less efficient, ranging between 10 to 14% efficiency, but has significantly lower manufacturing costs[38]. The visual differentiation between single-crystal silicon and polycrystalline silicon is presented in Exhibit 18.

Gallium-Arsenide (GaAs) is a compound semiconductor made of gallium (Ga) and arsenic (As). It has some electronic properties that are superior to those of silicon. It presents higher saturated electron velocity and electron mobility. Its electricity output to weight ratio is about 48 W/kg[39], 60% higher than silicon on average. Another advantage is that GaAs has a direct band gap, which allows for a much higher light absorption and higher efficiency, roughly 25 to 30%[40]. Its high resistance to heat is ideal for concentrator systems, and it has strong resistance to radiation, generating less noise when operating at high frequency. These characteristics make it a strong candidate for space applications[41]. However, GaAs does have higher production costs when compared to silicon, because silicon is abundant in nature and relatively cheap to process. Moreover, GaAs panels are estimated to degrade at 2-3% per year in space[42]. Exhibit 19 depicts GaAs solar panels.

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37. Mah, O. "Fundamentals of Photovoltaic Materials", National Solar Power Research Institute, Inc. December 21,1998 (hereafter cited as *Mah, PV Materials*).
38. Mah, PV Materials.
39. NL, Power from Space.
40. Mah, PV Materials.
41. Mah, PV Materials.
42. NL, Power from Space.

Other crystalline materials include Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS). CdTe is the only thin film PV that is cheaper than crystalline silicon PV. However, it is not as efficient as polycrystalline silicon - the best cell efficiency achieved to date is 16.5% (see Exhibit 20 for a Diagram of CdTe photovoltaic cell composition). CIGS is mainly used in PV cells in the form of polycrystalline thin films, with best efficiency achieved of 19.5% (see Exhibit 21 for a diagram of CIGS photovoltaic cell structure).

Amorphous silicon (*a-Si*) is the non-crystalline form of silicon. *a-Si* has inferior electronic performance and is less efficient than crystalline materials. One advantage of *a-Si* is that it is more flexible and can be made thinner than crystalline silicon, therefore lowering material costs. It can also be deposited at very low temperatures, which favors its use in space, an almost perfect heat-sink location. Exhibit 22 presents a diagram of *a-Si* photovoltaic cell composition. Due to its inherent mechanical and chemical properties and resistance to radiation, GaAs is usually the compound that is chosen when evaluating SPS systems. The economic and financial viability analysis carried out herein uses GaAs as the chosen compound.

Solar Dynamic Systems

Solar dynamic systems concentrate sunlight into a receiver where solar heat is used to drive a heat engine connected to an electric generator. The system includes a solar concentrator, which collects sunlight; a receiver, which receives, stores, and transfers the concentrated solar energy; a Brayton heat engine, which generates electric power; and a radiator, which emits waste heat[43]. The receiver contains a phase-change salt storage material that absorbs energy and provides continuous heat throughout the orbit[44]. The Brayton heat engine is comprised of a

43. "Solar Dynamic Power System Development for Space Station Freedom." NASA Glenn Research Center, Staff of Solar Dynamic Power System Branch, May 1993 (hereafter cited as *NASA GRC, Solar Dynamic*).
44. NL, Power from Space.

turbine, a compressor, and a rotary alternator, and uses helium-xenon as the working gas. The helium provides superior heat transfer characteristics for the heater, the cooler, and the recuperator. The xenon gas adjusts the molecular weight to provide superior aerodynamic performance for maximized turbine and compressor efficiency[45]. A recovery heat exchanger between the turbine discharge and receiver inlet is often used to improve cycle efficiency. The gas expands through the turbine when heated, cools through the heat exchanger where waste heat is transferred to a liquid coolant, and pressurizes within the compressor. Waste heat is dissipated to space via the radiator. The rotary alternator typically provides three-phase, alternating current at about 1khz[46]. Exhibit 23 presents a diagram of solar dynamic system with water as the working fluid.

Compared to photovoltaic systems, this system can provide continuous power in LEO/MEO without electricity storage systems[47]. This system also has the potential to provide a much higher efficiency of 20-30%[48], and incurs lower maintenance costs[49].

Power Transmission

Radio Frequency

Radio Frequency (RF) is the transmission of electromagnetic waves with frequencies below those of visible light. It is generated by oscillations of electromagnetic fields. Current uses include audio, video, navigation, heating, etc. Wireless power transmission is an already validated technological breakthrough and has demonstrated high potential. In 2008, Dr. Neville

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45. Harty, R.B. Otting, W.D. Kudija, C.T. "Applications of Brayton cycle technology to space power." Aerospace and Electronic Systems Magazine, IEEE, 9 (1994): 28-32.
46. Mason, L.S. "A Solar Dynamic Power Option for Space Solar Power." NASA Glenn Research Center, last modified July 1999, http://gltrs.grc.nasa.gov/reports/1999/TM-1999-209380.pdf.
47. NL, Power from Space.
48. NL, Power from Space.
49. NASA GRC, Solar Dynamic.

Marzwell of the NASA Jet Propulsion Laboratory successfully transmitted energy via RF over a distance of 92 miles (148 km) and achieved greater than 90% conversion efficiency of energy to electricity[50].

The DC-to-microwave conversion system could be performed either by microwave tube system or semiconductor system, or a combination of both. The microwave tube generates high power microwave with high voltage, while semiconductor system generates low power with low voltage. Some commonly used methods of microwave tube include the Magnetron, the Traveling Wave Tube Amplifier (TWTA), and the Klystron. A comparison between different types of systems is shown in Exhibit 24. The microwave tube is more economical compared to semiconductors[51]. In addition, microwave tubes have a higher power-weight ratio than semiconductor amplifiers[52]. For the same amount of power generated, microwave tubes would be lighter and more feasible in a SPS system, where weight is an important issue to be considered, due to the major role that launching costs play into the economic and financial feasibility of SPS systems.

The transmission is done through an antenna. The antenna could be of any kind, but has to be a phased array. The phased array generates the beam with specific shape and direction and can steer the beam if needed. A comparison of different kinds of antennas is shown in Exhibit 25. The antenna array has to be very large (> 0.5 km in diameter) and therefore requires large on-orbit weight. It is a key driver of whole system mass and as a result it is not very plausible for

50. PG&E PPA.
51. Shinohara, N., "Wireless Power Transmission for Solar Power Satellite." Georgia Institute of Technology, accessed November 17, 2010, http://www.sspi.gatech.edu/wptshinohara.pdf (hereafter cited as *Shinohara, Wireless Power*).
52. Shinohara, Wireless Power.

small amounts of power[53]. The frequency of RF used in wireless transmission of power would be 2.45 or 5.8 GHz[54]. The beam towards the Earth would be at an intensity of about 1/6 of noon sunlight, delivering 5-10 GW of electricity[55]. As previously mentioned, a rectifying antenna, or rectenna, is the method of power reception.

Laser Beams

The use of laser to transmit power was first proposed by Grant Logan in 1988, with technical details worked out in 1989[56], but the high cost of taking the concept to operational status and the distant payoff horizon halted the development of the technology[57]. A large-scale space demonstration is yet to be done. Exhibit 26 depicts what the space demonstration would look like. Laser beams have much shorter wavelength and as a result can be done through much smaller apertures. This characteristic allows achieving first power at much lower on-orbit weights, and much smaller receiver site on earth. A tuned photovoltaic arrays or solar dynamic engines are the ground receivers.

The main disadvantage would be that laser beams have lower efficiencies both in generation and reception. It is less mature at high power levels, and may have eye-safety concerns and be unacceptable to the public[58]. The perceived risk of such an exposure by the general public could create negative public perceptions around the technology, and NIMBY manifestations could take place, causing the complete stoppage of the development of the power-receiving site.

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53. NSSO, SBSP.
54. Shinohara, Wireless Power.
55. PG&E PPA.
56. Landis, G. A., "My Involvement with Laser Power Beaming", Geoffrey A. Landis Website, last modified March 6, 2011, http://www.geoffreylandis.com/laser.htp (hereafter cited as *Landis, Laser Power Beaming*).
57. Landis, Laser Power Beaming.
58. NSSO, SBSP.

Earth-to-Orbit Transportation (ETO transportation)

It is argued that direct launch from Earth to Orbit using chemical propellants may be possible, but highly undesirable due to their low efficiency levels. A nodal architecture would be preferred, with earth to low-earth orbit as one segment, followed by LEO to geostationary orbit (GEO) segment. The heavy lift launch vehicle (HLLV) would rely on a two-stage-to-orbit (TSTO) approach. Reusable launch vehicles (RLV) can be used from earth to LEO. RLV could be either a two-state-to-orbit (TSTO) rocket powered vertical launch horizontal landing (VTHL – Vertical Take-off Horizontal Landing) system, or a Maglev assisted air-breathing or airborne oxygen enrichment horizontal takeoff and landing (HOTOL) system. Examples of VTHL, HOTOL, and VTL are shown in Exhibit 27. Solar Electric Transfer Vehicles (SETV) would then be used to transport from LEO to GEO. These infrastructures would require an extensive amount of operations and maintenance, but a certain number of earth to space launches would make these systems viable, as the cost of the RLV would be amortized over many launches, therefore lowering the total cost of launching SPS systems to space.

Other suggested options include gun launch using a space elevator, and a magnetic levitation launcher (Maglev), shown in Exhibit 28. Space elevator is the most commonly studied non-rocket space launch means. First proposed by Konstantin Tsiolkovsky in 1895, the operating principle of the space elevator is similar to the operation of a regular apartment elevator, with a physical structure providing guidance for the launching of objects. While some concepts are considered technologically feasible nowadays[59], the gravitational field of the Earth is too strong, and there are no engineering materials that are sufficiently strong and light to enable this concept

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59. "Audacious & Outrageous: Space Elevators." NASA Science News, accessed March 27, 2011, http://science.nasa.gov/science-news/science-at-nasa/2000/ast07sep_1/.

to be developed on earth. Maglev systems have been first patented in 1907. Since then, a number of developments, mostly of trains, and extensive testing has been carried out, with top speeds of 581 km/h (361mph) having been reached in Japan in 2003[60]. The most well-known implementation of high-speed Maglev is the Shanghai Maglev Train, that transports people 30km (19mi) to the airport in roughly 7 minutes, with top speed of 431km/h (268mph) and average speed of 250km/h (160mph)[61].

ECONOMIC VIABILITY OF SPS SYSTEMS

Most of the issues in evaluating SPS' business viability are related to various costs, which are sometimes seen as impediments for this technological breakthrough to be widely accepted and supported, both by governments and by the private sector. The assumptions used to develop a financial model to assess the financial opportunities associated with building, launching, and operating a SPS are now presented, together with model results and sensitivity analyses.

Other important issues currently faced by the energy industry, which have already been discussed, range from environmental impact (greenhouse gas emissions, pollution, and the need to handle nuclear waste), to social impact (moving populations to build hydro power plants, or the cannibalization of highly productive land to produce biofuels instead of food, in a world where almost one billion people are undernourished), and potential conflicts between neighbor nations for natural resources (both energy-related commodities and highly desirable real estate for hydro, solar, or wind power). The eventual exhaustion of fossil-fuel reserves and the real

60. "Maglev transport." Wikipedia, accessed March 27, 2011, http://en.wikipedia.org/wiki/Maglev_(transport)#Existing_maglev_systems.
61. IBID.

estate issues mentioned before support a definitive, reliable, sustainable solution to be established that refrains from security, social, political, and environmental issues.

And although the costs associated with developing, launching, and maintaining Solar Power Satellites have been labeled by some impeditive, this may not be true in the following possible future scenarios:

- Electricity prices are expected to rise, due to the increasingly greater demand by emerging economies and the potential exhaustion of readily and cost-effectively available natural fossil-fuel reserves, which will automatically make other alternatives for power generation more attractive, especially the SPS;
- International agreements may provide further incentive for countries to reduce their carbon emissions, which could further impact the cost of available sources of electricity. This increase in current available power option costs would further draw attention to a truly exogenous solution, the SPS;
- There are several possibilities for governmental subsidies to support the development of the SPS system, including energy security funding sources or a similar treatment given to other sources of energy (like nuclear, solar, or wind power) – either in terms of funds to be made available for major developments or in terms of tax holidays for firms that invest in these technologies;
- Earth-to-Orbit transportation costs are expected to be considerably reduced due to the entry of private firms into this sector, which has begun by this writing. The order of magnitude of this reduction remains unclear, but scientists and other specialists state that costs can be lowered by several orders of magnitude. This expected transportation cost reduction

would signal the maturity of this technology and assure that SPS can be a profitable venture, as will be seen in the sensitivity analyses below;

- SPS could last longer than previously estimated. It is common practice in the aerospace industry to conservatively choose a set of assumptions satisfying operating conditions of equipment in space. This is because scientists want to have their tests carried out in space with a high degree of certainty, with the result that most space-equipment has actually been over-designed, and has often provided more benefits than they were expected to. In this sense, it is possible that the degradation of SPS, initially estimated to range from 2-3% per year (leading to an average life of power generation of roughly 40 years) could be much lower, boosting the operational life of the SPS and leading to longer-lasting streams of revenues from the sale of electricity and, therefore, a greater financial return than initially anticipated.

Assessment of Prices

Exhibit 14 presents the average retail price of electricity in the U.S. by state in 2009. Since the cost of generation and transmission of power generated by a Solar Power Satellite does not vary depending on the location on Earth to which electricity is beamed, the operator of a SPS can take advantage of these different retail prices of electricity practiced across different locations. For example, by beaming power to Hawaii, Connecticut, Alaska, New York State, and Massachusetts, the average price per KWh that an operator of a SPS can reach is of 19+ cents. It is important to note, however, that Exhibit 14 presents data for the U.S. only. The average retail price per KWh of electricity in the U.S. is $0.115 cents. Worldwide electricity prices vary even more widely. Exhibit 15 presents electricity price data around the globe. Although these are the prices that utility companies charge industries (and therefore they are lower than average price), it is noticeable that SPS's can capture the upside of selling large amounts of electricity to heavy industrial users in Japan, Italy, or Nicaragua at a 15+ cents per KWh, a 30% higher price than the average retail price charged in the USA, at current rates.

Exhibit 16 presents data on the worldwide average price of electricity, reinforcing that more isolated locations have a higher willingness-to-pay for readily available energy sources. The chart shows that two out of the three most expensive locations are in the Federal Territory of Nunavut in Canada. There, the price per KWh averages US$65 cents. The flexibility of the SPS systems enables its operator to take advantage of the surpluses in these isolated areas. One can expect the demand on those locations to be low when compared to well-developed countries. As per the chart on Exhibit 16, however, it is clear that well-developed countries with a large demand for electricity also have much higher average retail prices of electricity per KWh. This is the case in Denmark (42 cents), Ireland (27 cents), and the Netherlands (26 cents).

The possibility of capturing the consumer surplus or the higher willingness-to-pay for a cleaner, readily available source of energy around the globe is a major advantage of SPS systems versus other energy sources. The prices of electricity per KWh mentioned in the previous paragraphs will be of further help below, when sensitivity analyses are developed to evaluate the SPS economic and financial viability.

Assessment of Costs

This cost assessment is largely based on the assumptions adopted by the 2007 study conducted by Boeing entitled *Commercial Space Transportation Study*. The assumptions used in the base-case of the financial model of SPS systems are shown in Exhibit 29. These assumptions are based on a scenario in which technological breakthroughs have managed to lower launch costs to GEO to as low as $400 per kg. The suborbital space tourism market, spearheaded by Virgin Galactic, has helped the initial development of the space transportation market. Following the success of Virgin Galactic's spaceships, Elon Musk, founder of PayPal and Tesla Motors, realized that there is a possibility for the private sector to compete with government spacecraft also in the commercial and scientific space transportation market. He started SpaceX to bring innovation to a market that has traditionally been dominated by governments and large aerospace companies. Following the retirement of the Space Shuttle, he expects to be able to make space transportation immensely cheaper than the current governmental costs of launching and operating spacecraft per kilogram of space cargo.

Even with such an optimistic scenario launching costs would still represent 77% of the total cost-to-first-power of an SPS. Boeing estimates that one 11.4GW Solar Power Satellite system would cost $5,044 million, while its receiving antenna would cost roughly $7,243 million, totaling roughly $12.3 billion in hardware costs. Meanwhile, the transportation costs into space would total $40.3 billion, given the total structural weight of the SPS of roughly 54,331 metric tons and a launch cost of $400 per kilogram of hardware to be transported into space[62].

Financial Model

Given the assumptions presented in Exhibit 29, a financial model was developed, assuming that all of the power generated by the SPS and received by the rectenna would be sold at an average retail price of ¢11.51 of US$, the average residential retail price in the U.S.A. in

62. "Commercial Space Transportation Study." The Website of NASA HQ, Chapter 3.8.2.2.2.3.3, Boeing, last modified January 4, 1997, http://www.hq.nasa.gov/webaccess/CommSpaceTrans/ (hereafter cited as *CommSpaceTrans*).

2009, according to the U.S. Energy Information Administration[63]. Other assumptions include U.S. corporate tax rate of 35%, a discount rate of 7%, and SPS lifetime of 40 years (i.e. 2.5% degradation of solar cells per year).

Exhibit 30 presents the financial model's base-case, and its respective Net Present Value (NPV) and Internal Rate of Return (IRR). The resulting negative NPV of ($21.8) billion might seem like a bad deal for such an innovative technology. However, nuclear fusion power, for example, has received the sum of $21 billion in government funding[64]. If this amount of funding had been made available to SPS developers, the NPV of the SPS systems would be approximately at its breakeven point. However, this forecast scenario could still be much rosier, if certain favorable conditions materialize, such as:

- Governmental subsidies, either in form of technological funding or tax holidays;
- Power provision only to the spot market;
- Rising costs of energy-related commodities and, consequently, of existing power generation methods;
- More than one satellite is produced, amortizing the development costs that totals $8 billion over more units, and substantially reducing the development costs allocated to each satellite; and
- The potential establishment of price surcharges for polluting fossil-fuel power generation technologies, so as to cover costs associated with pollution and other socio-environmental side effects of these power sources.

63. "Electric Power Annual – Average Retail Price of Electricity." U.S. Energy Information Administration, accessed March 7, 2011, http://www.eia.doe.gov/cneaf/electricity/epa/epat7p4.html.
64. NSSO, SBSP.

In order to further investigate the effect of each of the variables that compose the financial model of the SPS systems, the next subsection presents a series of sensitivity analyses aimed at presenting possible scenarios in which the space-based solar power concept could bear fruit, while generating a positive financial return, creating proprietary intellectual knowledge and transforming the energy industry into a purely exogenous, truly sustainable endeavor.

Sensitivity Analyses

In each of the sensitivity analyses presented in this subsection, two of the base-case model assumptions were varied while the others remained constant. The intention of each such analysis is to investigate under which conditions an SPS system could yield positive financial return to a prospective investor in this technology. Following these analyses, the next subsection will present some possible future scenarios which could favor the adoption of SPS systems.

Discount Rate and Corporate Tax Rate

In the first sensitivity analysis both the discount rate and the corporate tax rates were varied. The real discount rate is being varied from 9% to -9%. This intends to capture the potential downside of a higher-than-expected discount rate, but it also tries to capture the potential upside from lower discount rates. The negative real discount rates reflect the possibility that inflation is higher than the interest rate. In this case, the real discount rate being negative means that there is an indirect subsidy being employed either by the country's central bank or by another potential governmental lender. This was the case during the South Korean boom from the early-70s through the early-90s. Exhibit 31 shows a chart of the real interest rates in South Korea during this period. These Korean subsidies were intended to boom inland investments and drive indigenous industries into an unprecedented growth cycle.

The other assumption that was varied simultaneously was the corporate tax rate, which started at a 35 percent standard rate and was varied down to zero percent, indicating the maximum tax holiday possible to be given as an incentive to this clean energy source. It is important to note that effective tax rates of major conglomerates in the U.S.A. have been low due to enormous benefits, as exemplified by GE, which from 2007 through 2009 had average effective tax rates of only 7%[65].

The output of this sensitivity analysis is presented in Exhibit 32. From this analysis it becomes clear that if governments were willing to adopt economic measures similar to the ones adopted by Korea in the past so as to incentivize the space-based solar power industry, such a venture could become profitable even at a full corporate tax rate of 35%. However, a

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65. "GE Tax Rate Shows Hypocrisy of Obama's Energy Tax Plan." FuelFix Website, accessed March 6, 2011, http://fuelfix.com/blog/2011/02/14/ge-tax-rate-shows-hypocrisy-of-obamas-energy-tax-plan/ (hereafter cited as *GE Tax Rate*).

compromise between low rates and tax holidays could be achieved, so as to minimize the total impact from the government perspective of these industry incentives and subsidies. For example, for an effective tax rate of 10% (slightly higher than the real rate for GE, for example) and a discount rate of 5% the SPS becomes a profitable project, if the other assumptions are held constant. This is certainly not an extreme measure, and could help make solar power satellites economically and financially viable.

Retail Price of Electricity and Launch Costs to GEO per kg of Mass Transported

SPS systems have the possibility of selling energy in the spot market and the flexibility to deploy and utilize energy all over the world, depending solely on the installation of a receiving antenna (rectenna). This enables SPS electricity to be beamed where it is most needed, or where its operator deems it most profitable. Some countries mentioned above have high electricity costs per KWh (i.e., the potential revenues per KWh sold for those countries), ranging from US$0.1151 (average retail price in the U.S.) to US$0.6534 (retail price in the federal territory of Nunavut in Canada). Between these two numbers, a series of other possibilities were considered, including selling energy to selected states within the USA (New York, Connecticut, Massachusetts, Alaska, and Hawaii) and selling electricity to countries with high demand and high prices in Europe (e.g., France, the Netherlands, Germany, Italy, and Denmark). Moreover, use of energy for military applications is more expensive. Charania et al (2010) calculated that the real costs per KWh consumed by the US military in their missions in Iraq and Afghanistan are US$0.92 and US$1.16 respectively[66]. Possible such military applications have also been considered in the present sensitivity analysis.

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66. Charania, A.C. et al, "A rational roadmap for developing a first revenue space solar power satellite". SpaceWorks Engineering, Inc., accessed March 7, 2011, http://www.sei.aero/eng/papers/uploads/archive/IAC-10.E6.3.11.pdf.

The second assumption that was studied simultaneously was the launch costs to GEO. Starting with the premises set forth by spacecraft currently under design by SpaceX, and the NASA agreement to use SpaceX spaceships to the next space missions, it has been determined that the best current price per kilogram launched into GEO is US$4,872[67]. This price has been brought down to a small fraction of this, following expectations of studies recently carried out by Boeing and NASA and arriving at a target price per kilogram of US$400[68].

With the other assumptions held constant as per Exhibit 29, the outcome of this sensitivity analysis is presented in Exhibit 33.

Price of Electricity Growth and Longer than Anticipated SPS Lifespan

Two other important variables to be considered are the ones that answer to the following hypothetical questions: "What if the retail price of electricity continues to grow?", and "What if the SPS lasts longer than it has been anticipated?". The former intends to address the phenomenon currently observed around the globe. For example, average retail price per KWh has more than doubled in Germany (and several other European countries) over the past five years, leading us to believe that this trend may be ongoing. Starting from the basic assumptions adopted for the initial financial model, retail price growth has been considered a minimum of 2% annually (i.e., the average retail price of electricity in the USA would double in roughly 36 years) and a maximum of 18% per annum (it would double in roughly 4 years) over the course of the ten years considered in the financial model. The latter variable consists in determining what the benefit would be if the SPS lasted longer than its expected life of 40 years, i.e., if the

67. "Falcon Heavy Overview." Space Exploration Technologies Corporation, accessed March 7, 2011, http://www.spacex.com/falcon9_heavy.php#pricing_and_performance (hereafter cited as *Falcon Heavy*).
68. CommSpaceTrans.

degradation of the solar cells were lower in space than they are on the earth (which is a very reasonable assumption, given the working conditions in space).

Exhibit 34 plots the output of this sensitivity analysis. It can be quickly noticed that the growth in the retail price of electricity plays a major role in determining the economic feasibility of the SPS concept. Although a longer lifespan of an SPS is desirable, it is not a major factor determining its design. This is because the longer it is designed to last, the heavier it will be, and the transportation costs into GEO have been shown to be by far the most important cost component that can either enable or prevent SPS systems of becoming a real, viable energy source concept. Also, the financial benefit of a longer SPS lifetime is not as relevant as other benefits from lowering transportation costs or the growing worldwide retail price of electricity. This is because most of the cash flows from this longer lifespan are too far into the future and, for most realistic discount factors, they become practically negligible.

From the three sensitivity analyses presented in the previous subsections it can be noted that two variables are the most impactful ones and, therefore, these will be simultaneously varied in the next sensitivity analysis presented.

Price of Electricity Growth and Launch Costs to GEO

This sensitivity analysis considered current commercially available launch vehicles as the starting point for the launch cost variable. The maximum transportation cost to GEO considered in this analysis was for Delta IV, a US-American launch vehicle dated from 2002. With a total cost of US$155 million, and a payload to GEO that totals 10,843 kg, its cost per kg launched to GEO amounts to US$14,295. Other two existing launch vehicles were considered: SpaceX Falcon9, and SpaceX Falcon9-Heavy, whose costs per kilogram transported amount to US$11,966 and US$4,872 respectively. It is important to point out that the latter is still in fairly early stages of development, while the former is in late stages of testing. This is one of the possible reasons for such a great discrepancy between both costs. Other costs considered in the analysis are specialists' estimates of the cost reduction potential, taking into account not only technology advancements, but also potential economies of scale of several launches taking place in one year. This assumption is based in the fact that SPS systems will require several launches in order for a single solar power satellite to be transported into space.

The growth in the retail price of electricity considered a vast range of possibilities, from a more conservative approach, i.e. 6 percent per annum, to a more extreme price increase of 18 percent. Hence, price per KWh is assumed to double every 4 to 12 years, based not only in past data, but also in the future trend of power consumption, which will very likely force energy-related commodities into new record price levels.

From the output obtained from this sensitivity analysis (Exhibit 35) it is possible to conclude that if the energy industry sees a huge increase in its costs – either derived from the rising cost of energy-related commodities or from other factors (e.g., surcharges on polluting energy sources so as to cover socio-environmental costs associated with them or the annulment of tax holidays and other governmental subsidies towards some specific energy sources) – solar power satellites can become a viable alternative even at launching costs of US$4.9 k per kilogram of space cargo, associated with SpaceX's Falcon9-Heavy launch vehicle.

Based on the sensitivity analyses presented above, possible future scenarios can be drawn. These future scenarios are divided in two categories: high probability outcome and medium probability outcome.

Possible Future Scenarios

Two possible future scenarios are presented below. The sets of assumptions used, as well as the set of cash flows obtained, and the net present values and internal rates of return are presented in each of them. Furthermore, a critical analysis of the assumptions used and which other components could have been improved if one were to model a more optimistic scenario based on the two presented below is detailed.

High Probability Outcome

The first scenario is based on the assumption that the lowest possible cost to launch the SPS will be 20% lower than the one derived from the Falcon9-Heavy launch vehicle, which corresponds to roughly US$4.9k per kilogram of hardware transported into GEO[69]. This assumption is based on the fact that the price of US$4.9k per kilogram includes a healthy profit margin from SpaceX. Taking into account the need for multiple launch flights into GEO for an SPS to be operating in space, there might be economies of scale to be captured and reflected into the cost of launching a solar power satellite. Compared to the base-case model, three other assumptions were changed: the initial power price (in US$/KWh), the power price growth (in % per annum) and the satellite lifespan. For the initial power price, it was assumed that the SPS operator would beam its power to selected U.S. states (NY, CT, MA, AK, and HI) where the price of electricity per KWh consumed is the highest, therefore yielding the highest possible revenues from the U.S. market. The power price growth was assumed to be 4% per year in real terms. This corresponds to the assumption that prices will rise slowly, doubling within eighteen years. Finally, the lifespan considered was of 50 years instead of 40, i.e., 2% degradation of the

69. Falcon Heavy.

solar cells per year instead of the previously assumed 2.5%. The set of assumptions is presented in Exhibit 36.

Besides, it was assumed that governmental subsidies would take two distinct forms: tax holidays (effective corporate tax rate would be as low as GE's, i.e. 7%[70]) and a low discount rate would be offered (not as extreme as the negative rates in the Korean model of the 70s, but as low as 3% in real terms). The corporate tax rate assumed is realistic, as it resembles the benefits given to companies in similar industries. Given the current state of the economy and the FED rates that reflect this state, a 3% real discount rate is not infeasible or unrealistic, given that these types of projects are usually heavily supported by local governments. Nonetheless, no direct funding from the government was assumed, although this could be expected, given the strategic role that power from space can play in terms of energy security, technological advancement, proprietary knowledge, etc.

Exhibit 37 presents the financial model output. Even with no direct governmental subsidies, the model yields a positive NPV, indicating that, although the launch cost to GEO is still a major concern (as it amounts to US$340 billion in initial costs), the imminent rising cost of electricity allied with a strategic choice of markets to which power will be supplied turns space-based solar power into an interesting alternative. The IRR is approximately zero, because the initial cash outlays are extremely high, mainly due to the launch costs of the SPS to its intended geostationary orbit. Although this scenario seems positive, the initial sum needed for the SPS to become operational is extremely high under launch costs of currently available technologies.

70. GE Tax Rate.

Medium Probability Outcome

The second scenario differs from the first one basically in three aspects. First, the launch cost is assumed to be US$800 per kilogram of hardware to be transported to GEO. This represents a 100% higher cost than the one estimated by Boeing and NASA in their 2007 study entitled Commercial Space Transportation Study[71]. Nevertheless, it is still approximately 83% lower than the lowest cost estimated to be available in the near future for commercial hardware to be launched to space (SpaceX's Falcon9-Heavy, US$4.9k/kg). Second, the electricity price increase per year is assumed to be only 2%, as the SPS systems are expected to lower these price increases by introducing a new method for power generation, which can lower the impact in costs of other energy sources by lowering the demand for them. Finally, it was also assumed that costs associated with maintaining the SPS are expected to be growing at a 2% annual rate, similarly to the growth experienced by the average retail price in this scenario. This would reflect a natural tendency of cost increase as the technology ages. The effective corporate tax rate was assumed to be 20%, i.e., the SPS operator still enjoys some tax break, but not as high as the ones expected in the previous scenario. The real discount rate chosen was 7%, also much higher than the previous one, and a very likely discount rate to be used for this type of project.

As Exhibit 39 presents, this scenario yields a much higher NPV. However, the expectation that launch costs will be lowered by as much as 83% remains unclear, as there are no available mature technologies capable of achieving such low cost levels nowadays. Unless a major breakthrough is brought to the market (such as the ones listed in the present work on the Earth-to-Orbit Transportation section), this scenario does not seem to be realistic in the short-run.

71. CommSpaceTrans.

POLITICAL FEASIBILITY

The previous sections have described the energy industry as inherently endogenous. As such, although some benefits are achieved locally by some of the most recent energy sources, as a whole the game being played is a zero-sum game. Especially in the case of fossil-fueled power plants, the consumption of these energy-related commodities reduces the amount of these commodities available to others. And since most of the so-called green energy sources depend upon the same variable – environmental conditions (either sun or wind), whereas the older forms of energy source are the ones causing these environmental conditions to change, the only way for the energy industry to become a non-zero-sum game is for an exogenous alternative to come into play. By showing no direct dependency upon local environmental conditions, but rather by being dependent solely upon a constant solar influx that strikes Earth's atmosphere around the clock, Space-Based Solar Power offers the hope of transformation into a non-zero-sum game.

Using existing energy sources, an illustrative conceptual Pareto frontier can be built showing the trade-off between investment needed for a 1% GDP increase of a given country (given the direct relationship between economic growth and energy consumption growth shown in section 2) and the direct environmental impact per KWh of electricity generated (see Exhibit 40). In this chart, smaller values are preferred to large ones, since they present lower investment needed or lower environmental impact. Any of the solutions conceptually presented on the frontier can be described as Pareto-efficient outcomes. However some of the energy sources presented as Pareto-efficient might in fact not be so because the direct environmental impact (or risk) plotted on the x-axis is an ex-ante estimate of the impact caused by these power plants, and does not take into account potential catastrophic accidents that might take place. That said, it is important to reclassify some of the power sources as Pareto-suboptimal, so as to account for potential catastrophic failures of these plants, such as nuclear and hydropower. Ex-post, therefore, nuclear and hydro power could be seen as not belonging on the Pareto frontier due to the risk of radioactive leaks or dam ruptures, for instance. SPS has been presented in the Pareto Frontier chart for illustration purposes only because, as explained above, it has the potential of not being a zero-sum game player due to its inherent exogenous characteristics.

Government measures have deeply impacted the shape of this Pareto frontier, by enabling some power sources (through removal of tariffs, tax holidays, or other financial subsidies) to move towards the frontier, and broadening the portfolio of existing energy source options. The importance of governmental support, therefore, is paramount to the development of newer technologies that will enable a radical shift in the global energy landscape. This section presents recommendations that support the development of the solar power satellites and, simultaneously, move the current heavily endogenous power generation model into sustainable, exogenous, non-zero-sum game territory.

Political Support: Tax benefits, Government Funding, Public-Private Partnerships

Several countries have established a series of government support incentives to develop indigenous sources of renewable energy. This is the case of most European countries, the USA, India, and China, among many others. The energy security issue is still regarded as the most important problem to be solved by the global energy industry, and solar, wind, nuclear, geothermal, biofuels, and others are seen as promising in the movement towards energy sustainability. Worldwide tax benefits and government-sourced funding accounted for a total global investment in clean energy of US$155 billion in 2008[72]. The Obama Administration's American Recovery and Reinvestment Act of 2009 secured investments of up to US$70 billion in direct spending and tax credits for clean energy. Moreover, more than seventy countries have established some type of policy to promote renewable power generation[73].

While other sources of renewable energy, regardless of their endogenous influence over the environment, have been receiving such an enormous governmental support and funding, space-based solar power has received virtually none. More funding and support are crucial for the necessary technologies to be thoroughly developed and extensively tested, so as to ensure reliable applications of SPS systems in the near future. Due to lack of funding, NASA has decided to launch the Commercial Crew and Cargo Program to stimulate efforts within the private sector to develop and demonstrate safe and cost-effective transportation capabilities[74]. This solution has the potential to cost-effectively develop space transportation, given that this is the most important variable for SPS concept economic viability. SpaceX is one of NASA's partners in the development of new commercial launch vehicles, and has successfully launched its Falcon9 rocket on September 2010, which flew unmanned into orbit and returned safely[75]. This is a clear sign that the participation of private firms can drive innovation in a quicker way, so as to enable new breakthroughs, driving down costs and making it more likely that solar power satellites can become a reality.

72. "Clean Energy Trends 2009." Clean Edge Website, accessed November 17, 2010, http://www.cleanedge.com/reports/pdf/Trends2009.pdf.
73. Renewables 2010.
74. "NASA – Commercial Crew and Cargo." NASA Commercial Crew&Cargo Program Office, accessed March 7, 2011, http://www.nasa.gov/offices/c3po/home/.
75. "SpaceX Launches Success with Falcon9/Dragon Flight." NASA Commercial Crew&Cargo Program Office, accessed March 7, 2011, http://www.nasa.gov/offices/c3po/home/spacexfeature.html#.

Further government support is necessary, either in terms of funding and tax credits for the private firms, assets, or cash for this goal to be achieved. The total costs involved in the development of space-based solar power are extremely high and, therefore, countries have a strong incentive to cooperate in this process, given the global benefits an SPS can provide, not only in terms of the huge amount of energy readily available in space, but also in terms of reduction of environmental impact and other endogenous problems associated with the current model of power generation on Earth.

International Cooperation

"*When you are out in space, you don't see boundaries. You just see the beauties of the world.*" This was the opening statement of the keynote speech made by Dr. Bobby Braun, NASA Chief Technologist at the 13th Annual Emerging Technology Update Day at The Wharton School on Feb 25th 2011. At first, space exploration was perceived as a matter of honor. Capitalism fought against socialism for space supremacy. Getting there first was a matter of political superiority, pride. From the Soviets' launching of the first manned rocket into space and returning him safely to earth, to the Americans stepping first on the Moon, a huge technological leap was made, a scientific treasure that later directly influenced the rapid development of commercial aviation, telecommunications, and the health care industry, while helping other industries indirectly. With the fall of the Berlin Wall and the consequent disintegration of the Soviet Union, space was no longer a neutral location with bipolar 'owners', the Space Race was over. The collapse of the Soviet Union gave way to cooperation on space exploration: in June 1992 American President George H. W. Bush and Russian President Boris Yeltsin signed a cooperation agreement. This resulted in the International Space Station (ISS), primarily by the

USA and Russia, but later with several other countries joining (Japan, Canada, Belgium, Denmark, France, Germany, Italy, The Netherlands, Norway, Spain, Sweden, Switzerland, and the United Kingdom)[76].

Unofficial estimates indicate that a total of over US$100 billion might have been invested in the International Space Station over the course of two decades[77]. Although some countries have invested more than others (and also enjoyed more crew time, electrical power rights, and rights to purchase supporting services necessary for scientific research to be done in space, such as data upload and download), none of them would have been capable of carrying out these investments by itself. Nor would some of the recent scientific research initiatives have been carried out for lack of funds or infrastructure. This cooperation in space can be seen as a lesson for the future as not only risks and costs are spread out across different stakeholders, but also the benefits of multicultural development become apparent.

"*Fossil fuels were the energy source that shaped 19th and 20th century civilization. But burning coal, oil and gas has proved highly damaging to our environment. Carbon dioxide emissions, greenhouse effect gases, and fumes all contribute to the disruption in the balance of our planet's climate. Global energy consumption is set to triple by the end of the century. And yet supplies of fossil fuels are depleting and the environmental consequences of their exploitation are serious. Two questions loom over humanity today: how will we supply all this new energy, and how can we do so without adding dangerously to atmospheric greenhouse gases? No single nation can face these challenges alone.*"[78] – this is the statement that introduces the International

76. "International Cooperation." NASA - International Space Station Website, accessed March 9, 2011, http://www.nasa.gov/mission_pages/station/cooperation/index.html.
77. "What's the cost of space station?" The Website of MSNBC, accessed March 9, 2011, http://www.msnbc.msn.com/id/14505278/.
78. "The ITER Story." ITER Organization Website, accessed March 7, 2011, http://www.iter.org/proj/iterhistory.

Thermonuclear Experimental Reactor (ITER) project in its website. ITER is a large-scale fusion scientific project, aimed at producing ten times the energy it will consume in the fusion process. Scientific experiments are expected to start in 2019. Since this will be a very large-scale project, no nation dared meet the challenge by itself. Rather, the European Union, already a consortium of several nations per se, envisioned this project as a global collaboration effort, and invited other nations to participate. The ITER location is now under construction with financial and technological support from the European Union, the USA, China, India, Japan, Russia, and South Korea. Total costs are estimated to be of 10 billion Euros (or US$13.9 billion, as of Mar 13th 2011) for an estimated net output of 450MW of energy (production of 500MW with the consumption of 50MW).

Although the ITER project is still in its early stage of development, the great lesson learned is the rationale used in designing this joint effort: affording such an expensive, technically challenging power source by means of international collaboration among nations with aligned interests, i.e., to discover new, reliable, and sustainable energy sources. Coincidentally (or not), both examples of some of the world's largest international cooperation projects mentioned in the previous paragraphs (ISS and ITER) involve space exploration and power generation, the exact definition of what a Solar Power Satellite project should be based on.

CONCLUDING REMARKS

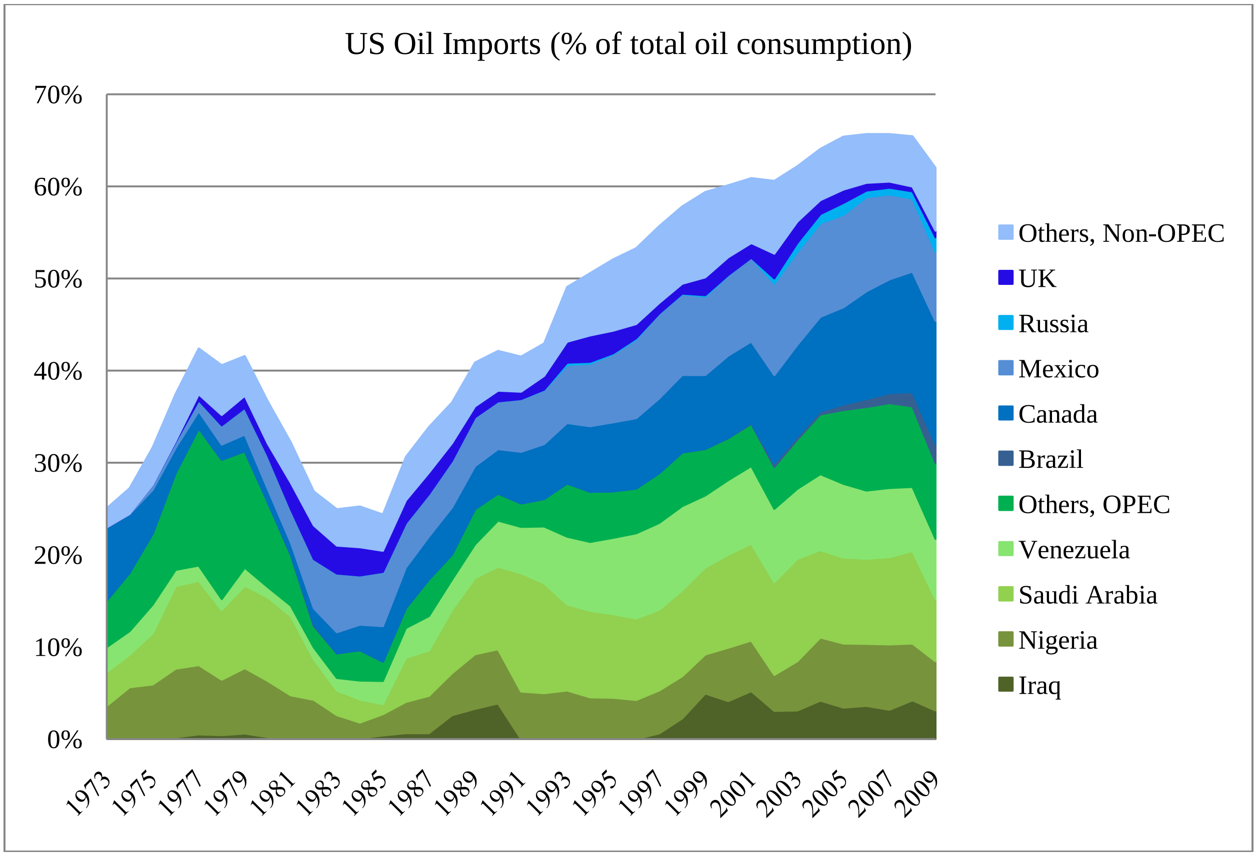
Space-based solar power has been studied only as a byproduct of the Space Race. In the 60s and 70s, innovation was fueled by the cold war, where political motivation made it easier for the Soviet Union and the United States to fund their space agencies. Several technological breakthroughs were originated from the Space Race of the late-60s, such as cutting-edge materials and fabrication processes, satellites and their direct influence over telecommunications, and medical research. However, the technologies available in the sixties were not enough for solar power satellites to be produced or even tested. The main technological breakthroughs needed for an SPS to become reality have already been at least partially achieved, such as wireless power transmission (or power beaming). Although there is definitely need for extensive testing and technology risk mitigation, at this writing there are no major areas of concern that would prevent solar power satellites from becoming a reality. The major restriction facing the development of SPS systems is related to earth-to-orbit transportation costs. And although private investors (such as Sir Richard Branson's Virgin Galactic and Elon Musk's SpaceX) have been exploring and innovating in this area – and thus lowering costs – there is currently not a readily available technology enabling affordable transportation to space, especially for a huge satellite that is supposed to weigh around 55 thousand metric tons.

However, the desirability of a purely exogenous energy source is real, and no other power source available or under development is capable of claiming to be not-purely-endogenous. As a result, although new power sources might be less polluting and less impactful than the more primitive energy sources still in use in most countries (such as the ones derived from fossil fuels), the already delicate state of the environment continues to worsen as time goes by. Moreover, all of the currently existing power generation options can be characterized as players of a zero-sum-game, i.e., they shift commodities and/or benefits from one side of the globe to the other, while potentially having negative environmental impacts. Issues currently faced by the energy industry worldwide point out to an increasingly need for a non-zero-sum game to be developed, allowing mankind to benefit from a new power source, without jeopardizing the environment or individual nations.

This paper has detailed several factors supporting SPS systems, either by governmental direct subsidies (funding), or by indirect support (tax holidays, lower interest rate on the necessary investments). Some possible scenarios have been presented, all of which illustrate the potential of the SPS concept, and the potential for investors who choose to undertake projects in this promising energy field. Finally, international cooperation has been pointed out as crucial for the success of any venture of this magnitude, given the sheer size of needed investments and the global potential of resulting benefits. The first Space Race, driven by two separate economies with much secrecy and no cooperation whatsoever, brought many benefits for mankind all over the world. A Second Space Race, aiming at discovering and exploring the virtually infinite source of solar energy available in space, is the only long-term feasible solution for the current global energy crisis. This solution causes no environmental harm, poses no threat to mankind on the surface of the earth, and is absolutely unique in one aspect: it is truly exogenous.

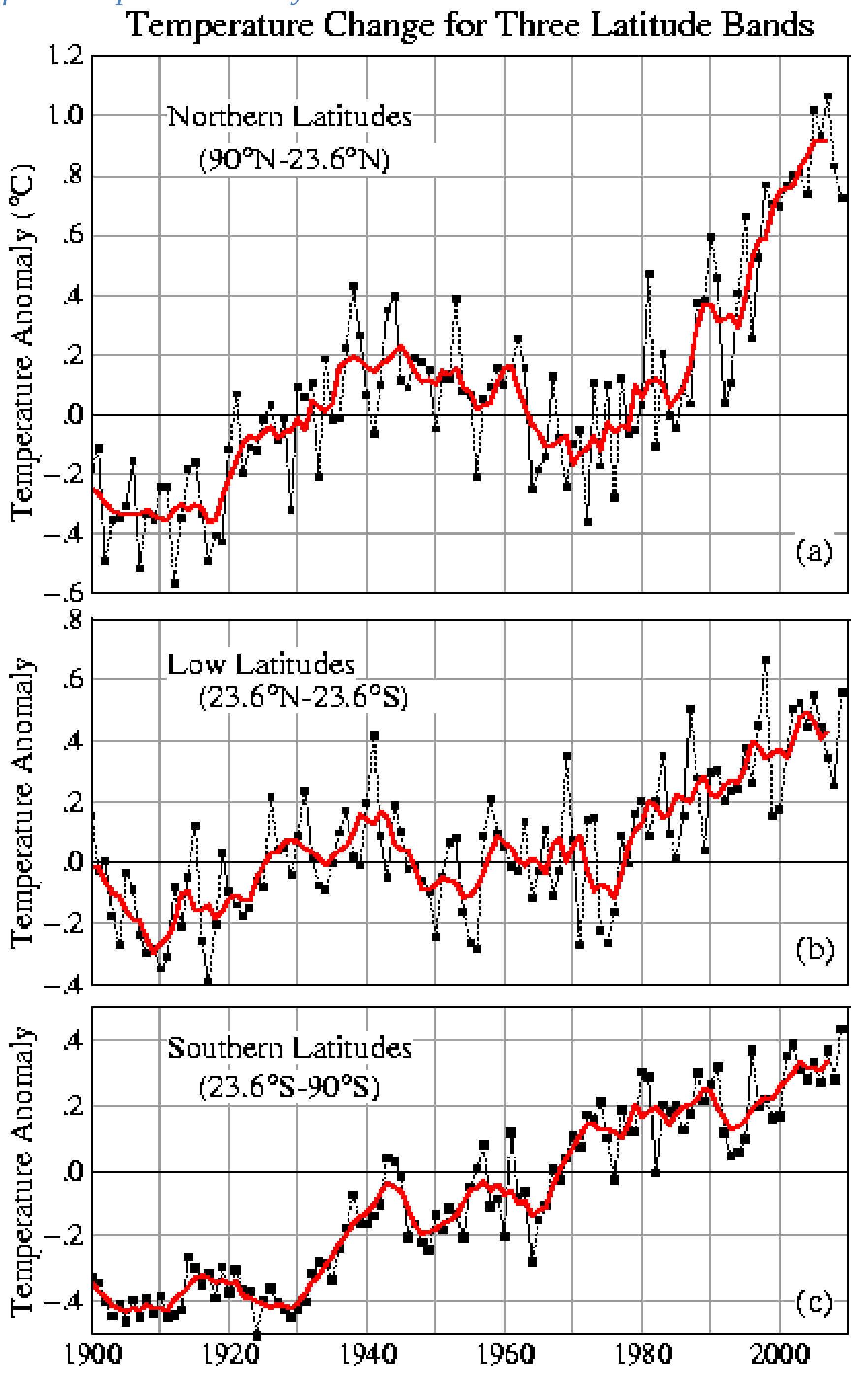
EXHIBITS

Exhibit 1 – U.S. Gross Petroleum Imports by country of Origin. Source: U.S. Energy Information Administration[79]; Analysis: Andre Soresini



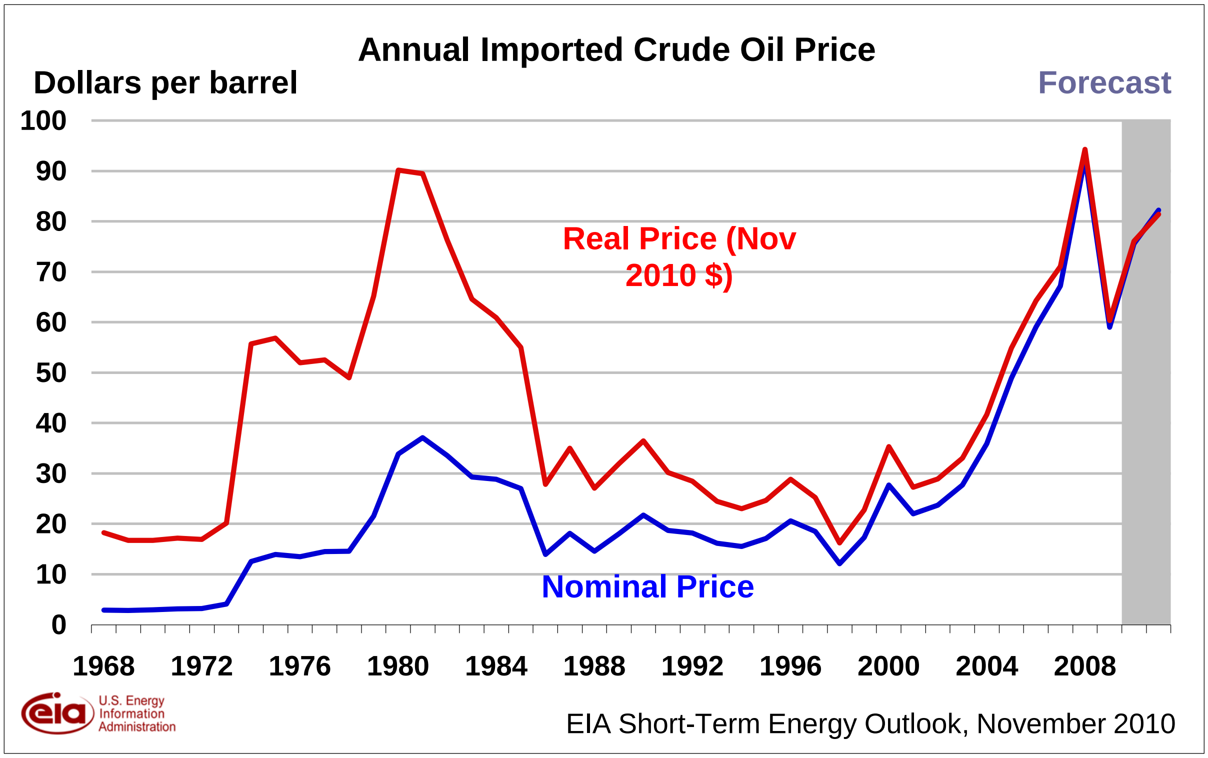
79. "U.S. Crude Oil Imports." U.S. Energy Information Administration, accessed September 19, 2010, http://tonto.eia.doe.gov/dnav/pet/PET_MOVE_IMPCUS_A2_NUS_EPC0_IM0_MBBLPD_A.htm.

Exhibit 2 – Surface Temperature Analysis. Source: NASA[80]



80. "Goddard Institute for Space Studies – Surface Temperature Analysis." NASA GGISS Website, accessed October 3, 2010, http://data.giss.nasa.gov/gistemp/graphs/.

Exhibit 3 – Nominal and Real Annual Imported Crude Oil Prices. Source: EIA[81]

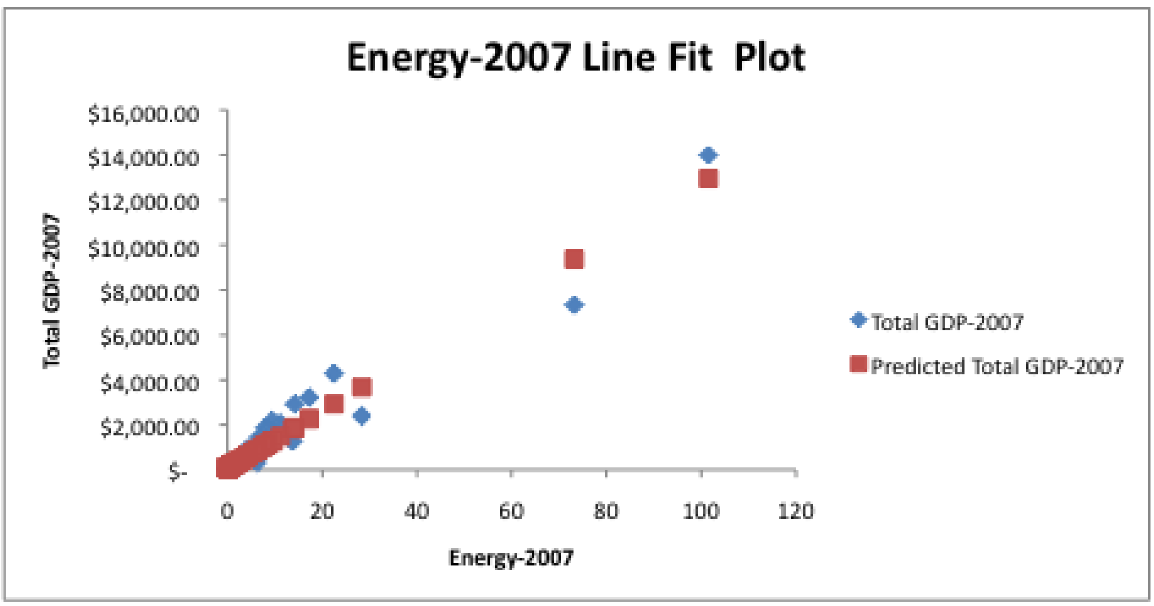


81. "Short-Term Energy Outlook – Real Energy Prices." U.S. Energy Information Administration, accessed September 19, 2010, http://www.eia.doe.gov/EMEU/steo/realprices/index.cfm.

Exhibit 4 – Total GDP (PPP) vs. Total Energy consumed (quadrillion BTUs) in 2007. Sources: World Bank[82], EIA[83]; Analysis: Andre Soresini

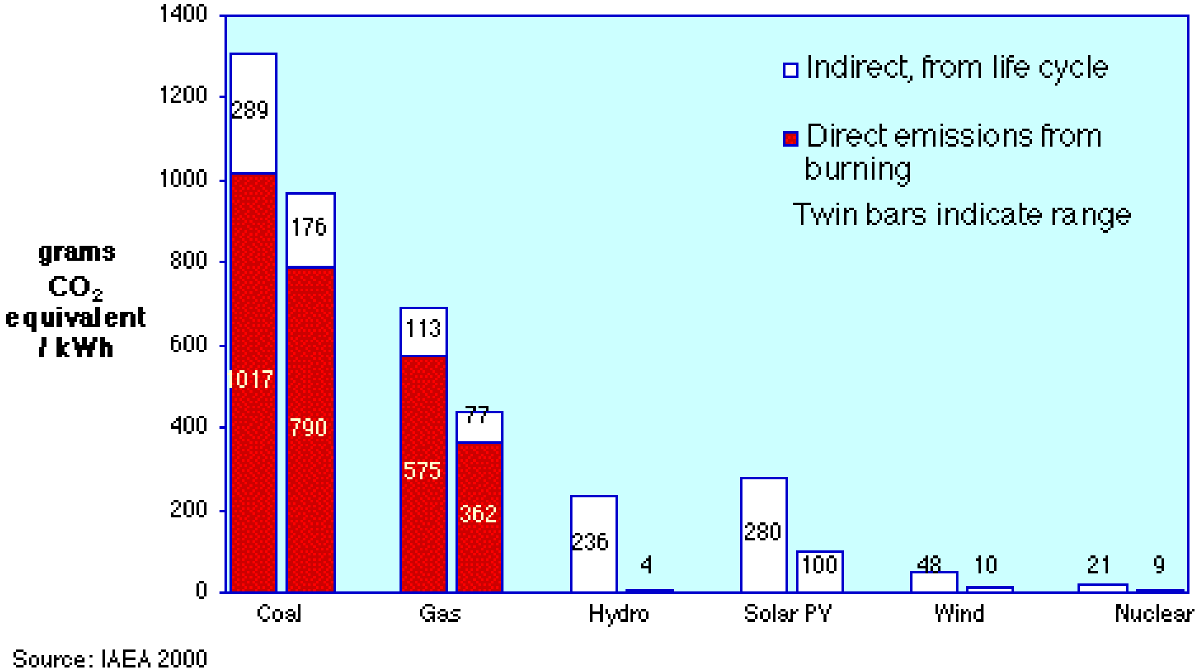
The following data for GDP in PPP terms is given in USD billion, whereas the total energy consumption is given in quadrillion BTUs.

SUMMARY OUTPUT				
Regression Statistics				
Multiple R	0.973258128			
R Square	0.947231383			
Adjusted R Square	0.946742785			
Standard Error	372.8124704			
Observations	110			
ANOVA				
	df	*SS*	*MS*	*F*
Regression	1	269454217.8	269454217.8	1938.671047
Residual	108	15010826.91	138989.1381	
Total	109	284465044.7		
	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	71.54623917	37.50015532	1.907891809	0.059060831
Energy-2007	126.8836224	2.881731453	44.03034234	8.01795E-71



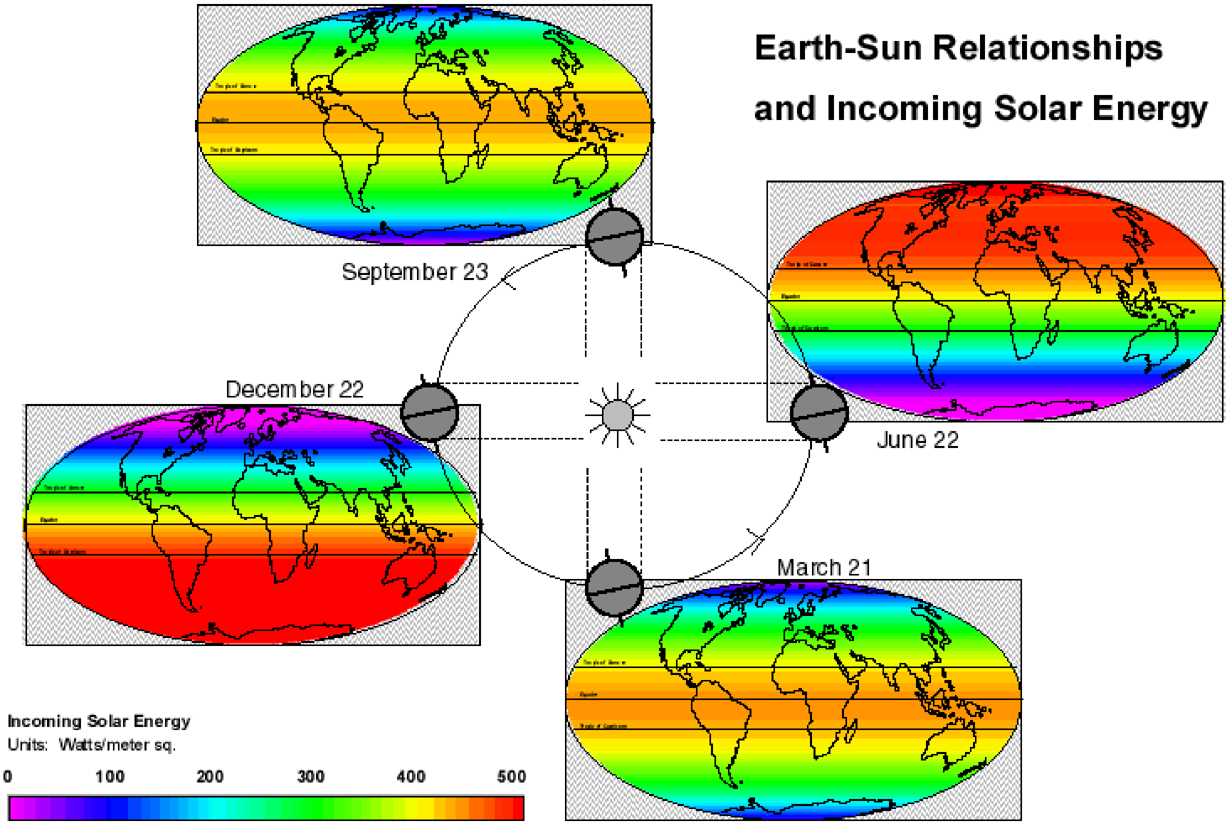
82. "World Bank Indicators – GDP (PPP) in constant international $." World Bank Data Center, accessed September 19, 2010, http://data.worldbank.org/indicator/NY.GDP.MKTP.PP.KD.
83. "International Total Primary Energy Consumption and Energy Intensity." U.S. Energy Information Administration, accessed September 20, 2010, http://www.eia.doe.gov/emeu/international/energyconsumption.html.

Exhibit 5 – Greenhouse Gas Emissions from Electricity Production. Source: World Nuclear Association[84].



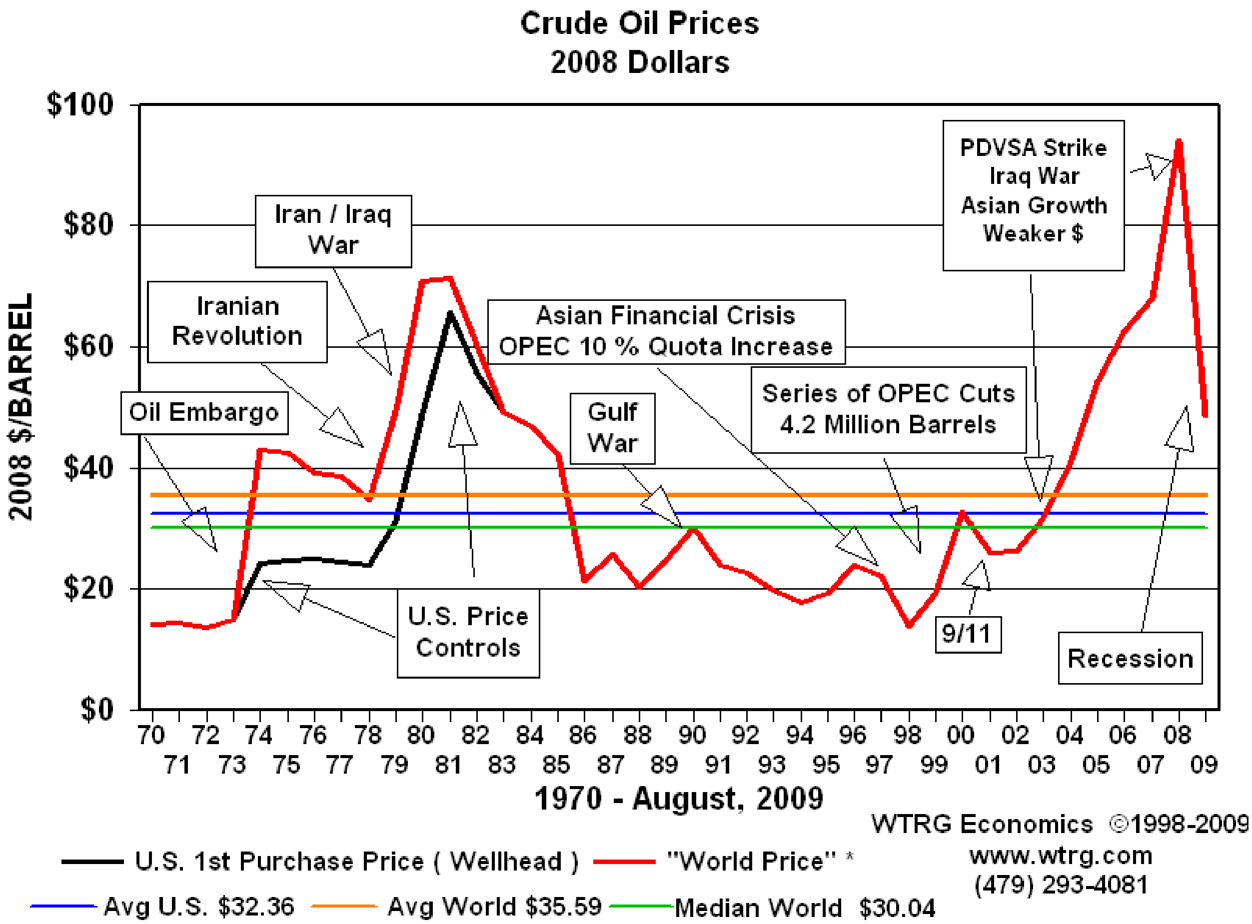
84. WNA, Emissions.

Exhibit 6 – Solar radiation on the surface of the earth[85]



85. "Earth-Sun Relationships and Incoming Solar Energy." Sharing of free intellectual assets (SOFIA) Website, accessed October 4, 2010, http://sofia.fhda.edu/gallery/geography/images/seasons_insolation.gif.

Exhibit 7 – Historical oil prices[86]



86. "Oil Price History and Analysis." WTRG Economics Website, accessed November 17, 2010, http://www.wtrg.com/prices.htm.

Exhibit 8 – The Sun Tower SPS Concept[87]

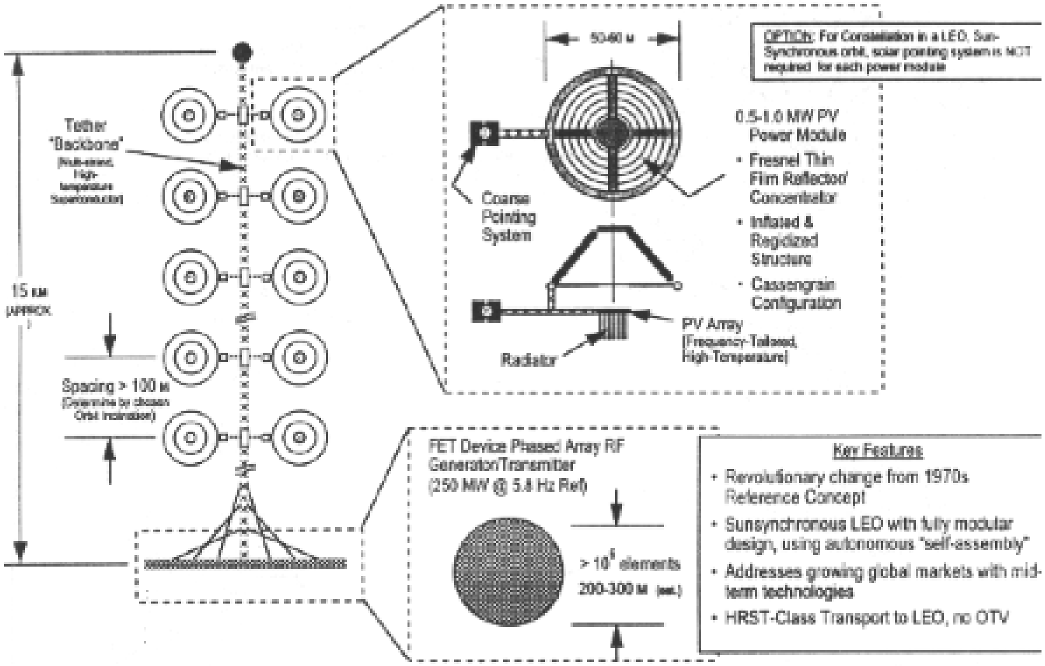
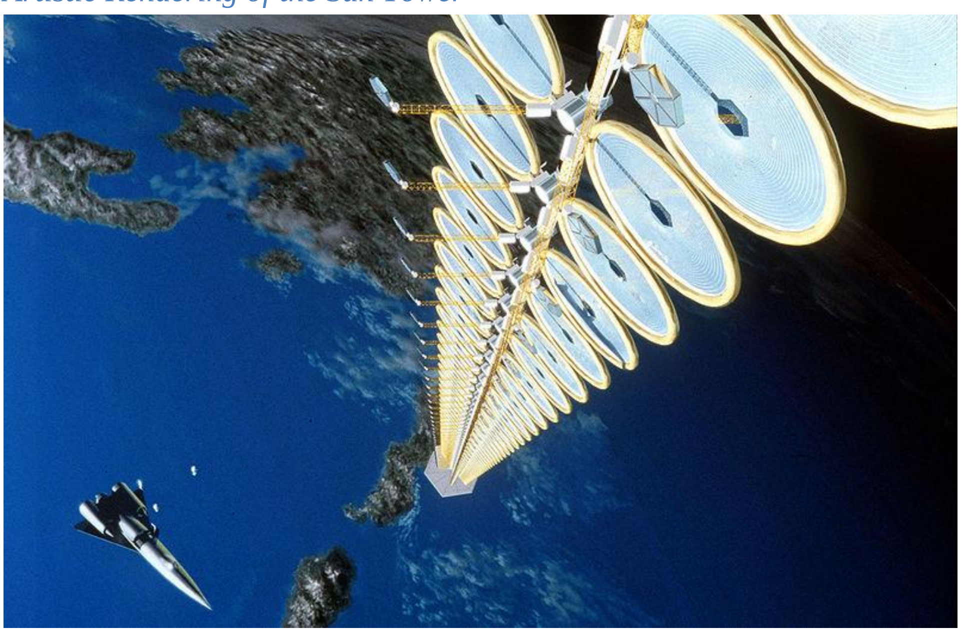


Exhibit 9 – Artistic Rendering of the Sun Tower[88]



87. Mankins, Fresh Look.
88. "Space Solar Power Satellites – Sun Tower." Innopedia Website, accessed January 17, 2011, http://innopedia.wdfiles.com/local--files/space-solar-power-satellites-with-power-beaming-to-aircraft/800px-Suntower.jpg.

Exhibit 10 – SPS power is beamed directly to a receiving antenna (rectenna)[89]

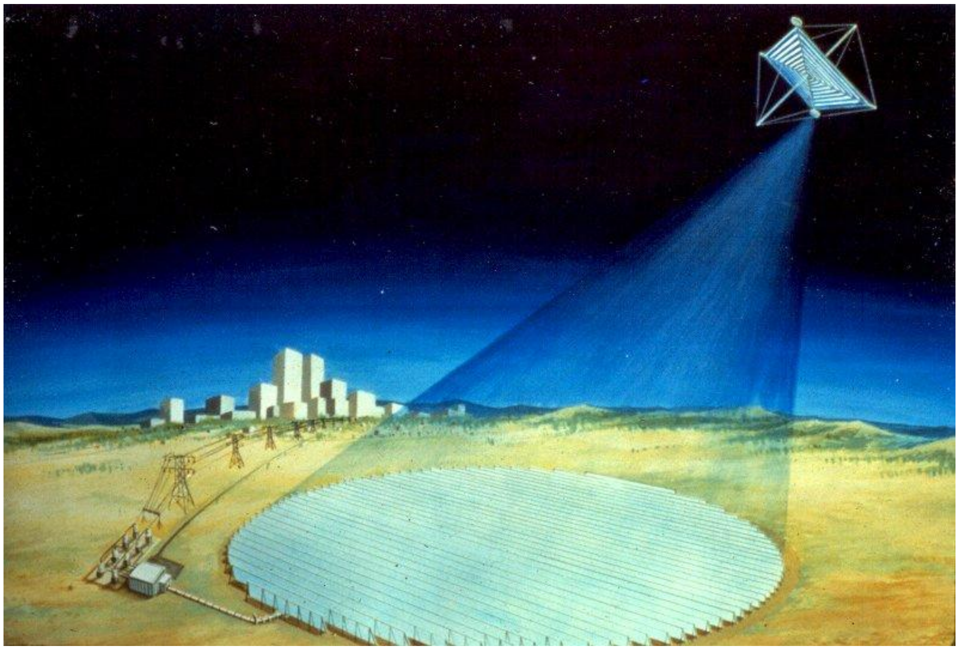


Exhibit 11 – A Rectenna could be located either in rural or urban areas[90]

89. "Solar Power Satellite – Rectenna." Space Studies Institute Website, accessed March 8, 2011, http://ssi.org/space-art/ssi-sample-slides/.
90. SSAG.

Exhibit 12 – The Solar Disc SPS concept[91]

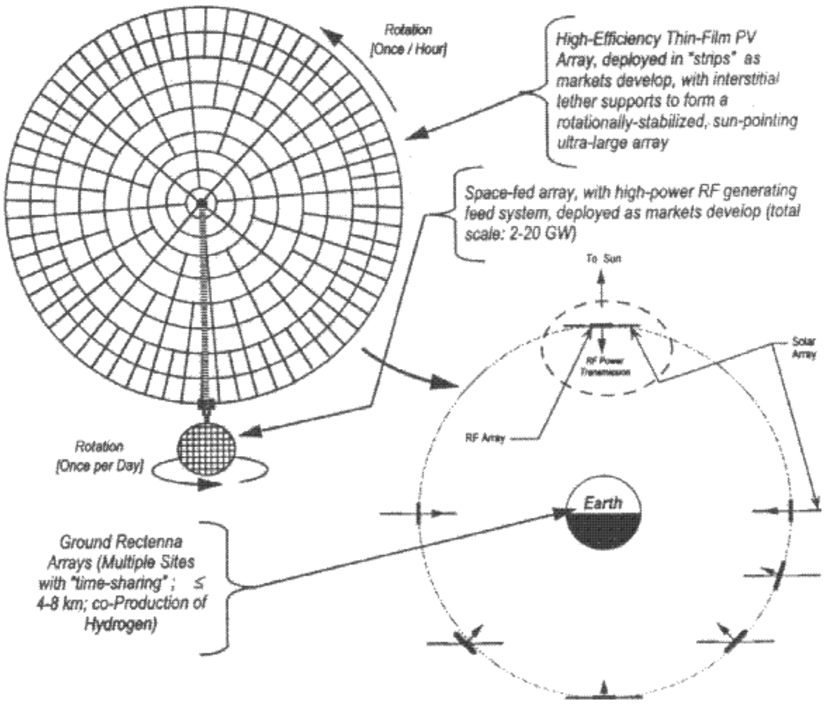
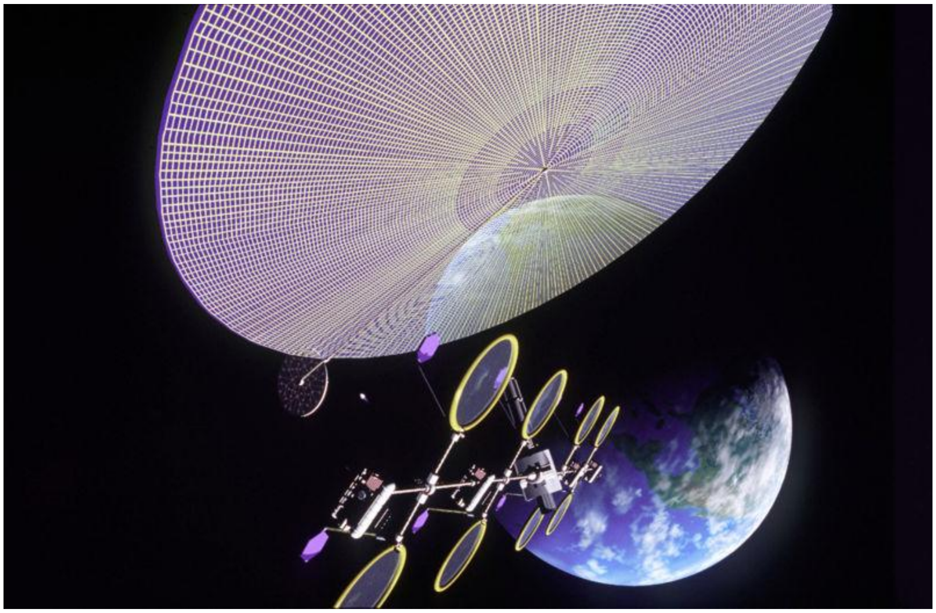
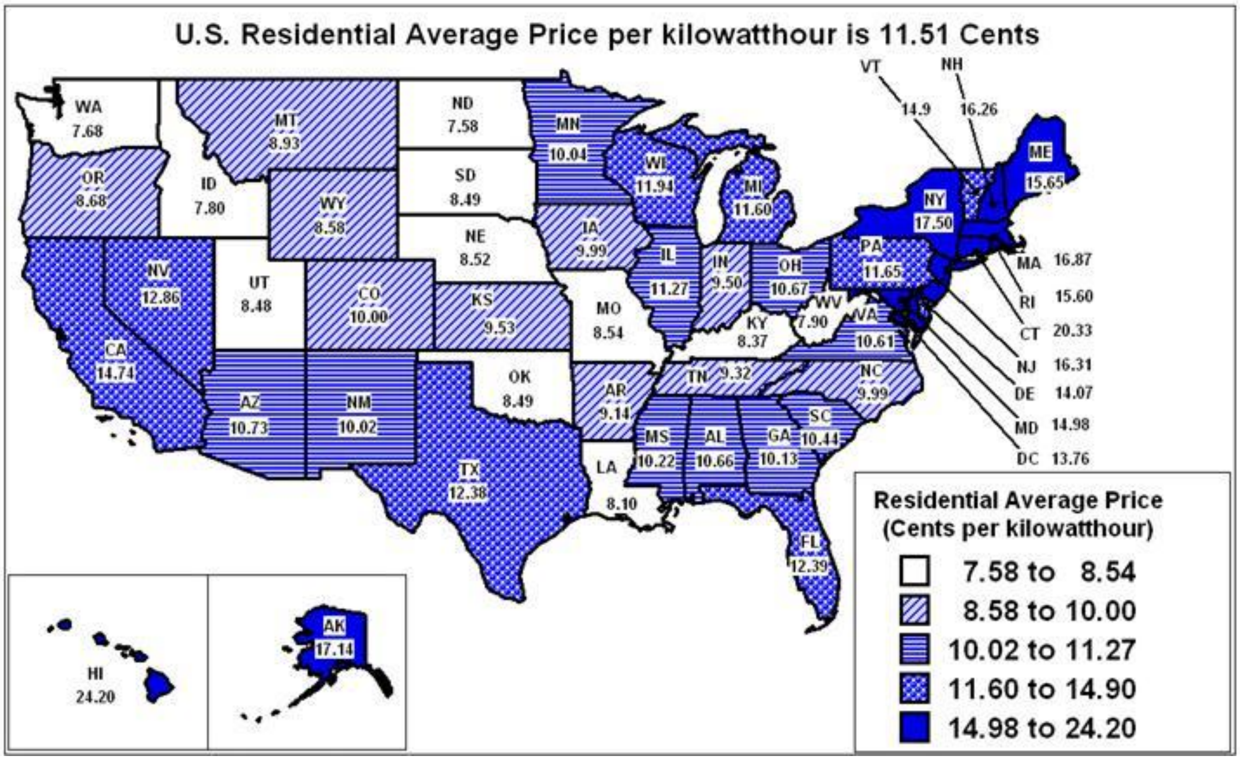


Exhibit 13 – Artistic Rendering of the Solar Disc[92]



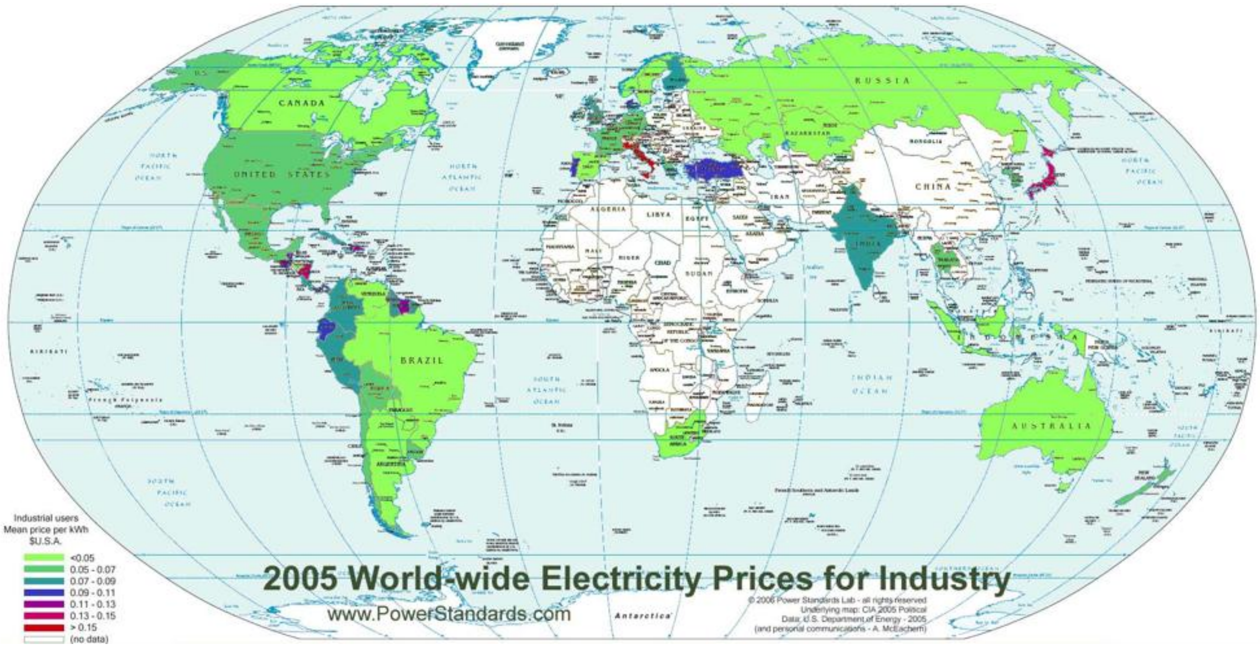
91. Mankins, Fresh Look.
92. "Space Solar Power Satellites – Solar Disk." Innopedia Website, accessed January 17, 2011, http://innopedia.wdfiles.com/local--files/space-solar-power-satellites-with-power-beaming-to-aircraft/800px-Solardisk.jpg.

Exhibit 14 – Average retail price of electricity in the U.S. in 2009[93]



93. "Average Retail Price of Electricity by State, 2009." U.S. Energy Information Administration, accessed March 7, 2011, http://www.eia.doe.gov/cneaf/electricity/epa/fig7p5.html.

Exhibit 15 – Worldwide electricity prices for industry[94]



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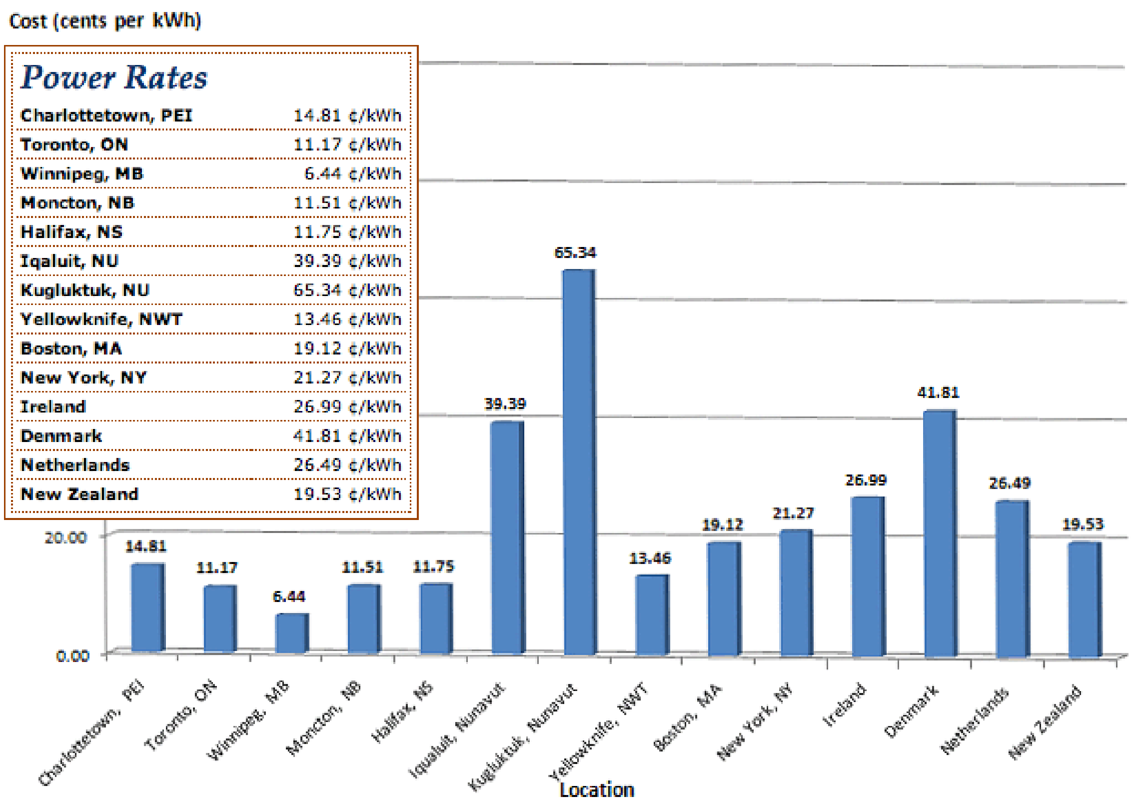
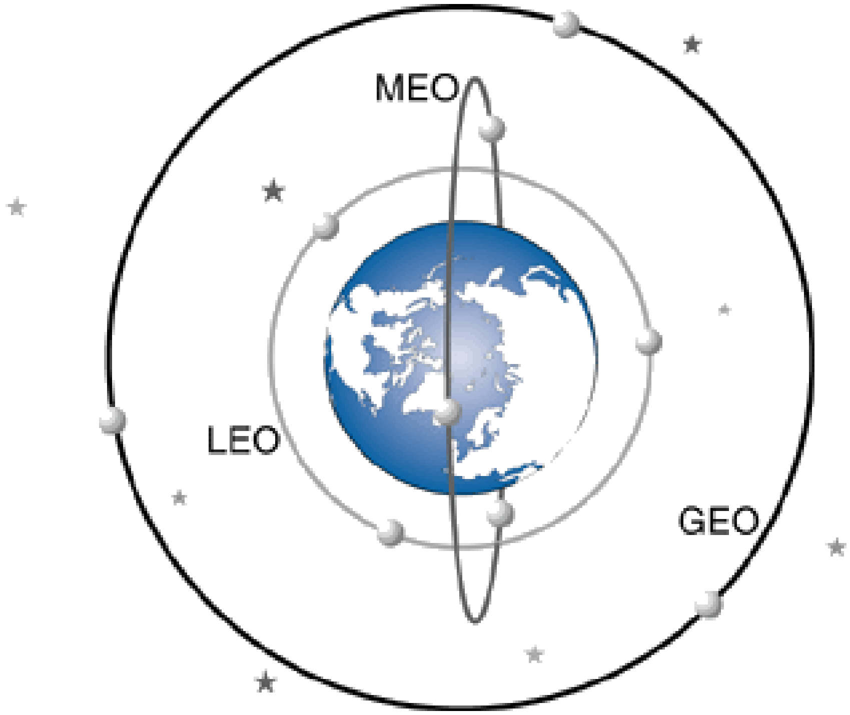
94. "Worldwide Electricity Prices for Industry." PowerStandards.com Website, accessed March 8, 2011, http://www.powerstandards.com/

Exhibit 16 – Average worldwide electricity prices[95]



95. "Electricity Prices Vary all Around the World." Maritime Electric Website, accessed March 8, 2011, http://www.maritimeelectric.com/understanding_electricity/el_comparing_prices.asp.

Exhibit 17 – Depiction of the three earth orbits[96]



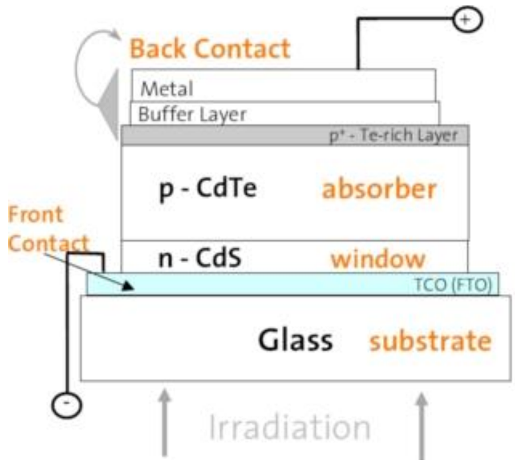
Orbit Distance	Miles	Km	1-way Delay
Low Earth Orbit (LEO)	100-500	160 - 1,400	50 ms
Medium Earth Orbit (MEO)	6,000 - 12,000	10 -15,000	100 ms
Geostationary Earth Orbit (GEO)	~22,300	36,000	250 ms

96. "Satellite Orbits." InetDaemon Website, accessed March 9, 2011, http://www.inetdaemon.com/tutorials/satellite/satellite-orbits.shtml.

Exhibit 18 – From left to right: single-crystal silicon[97] and polycrystalline silicon[98]

Exhibit 19 – GaAs-Solar Panels[99]

Exhibit 20 – CdTe Photovoltaic cell Composition[100]



97. "Monocrystalline and Polycrystalline Silicon Solar Cells." Rich Solar Website, accessed March 27, 2011, http://www.richsolar.com/de/product/Solar_Cells.htm.
98. IBID
99. "Top Advancements in Solar Technology – Gallium Arsenide Solar Cell." EcoFriend Website, accessed March 27, 2011, http://www.ecofriend.com/gallery/gallium-arsenide-solar-cell_69/.
100. "Cadmium Telluride Photovoltaic Film." MIT Fundamentals of Photovoltaics Website, accessed November 17, 2010, http://ocw.mit.edu/courses/mechanical-engineering/2-626-fundamentals-of-photovoltaics-fall-2008/chp_CdTe.jpg.

Exhibit 21 – GIGS Photovoltaic cell structure[101]

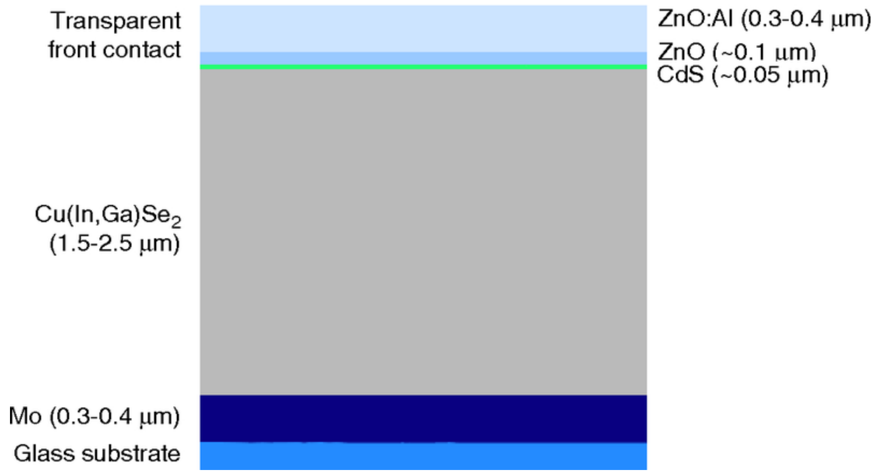
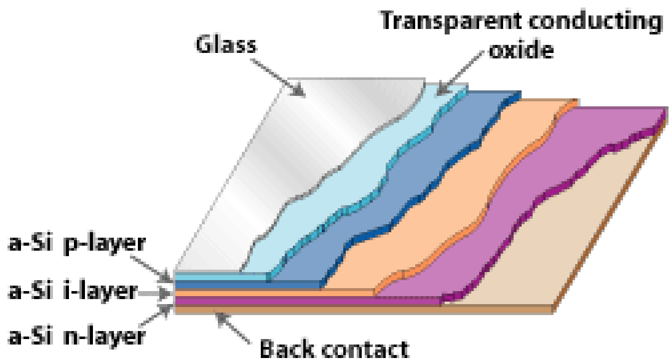
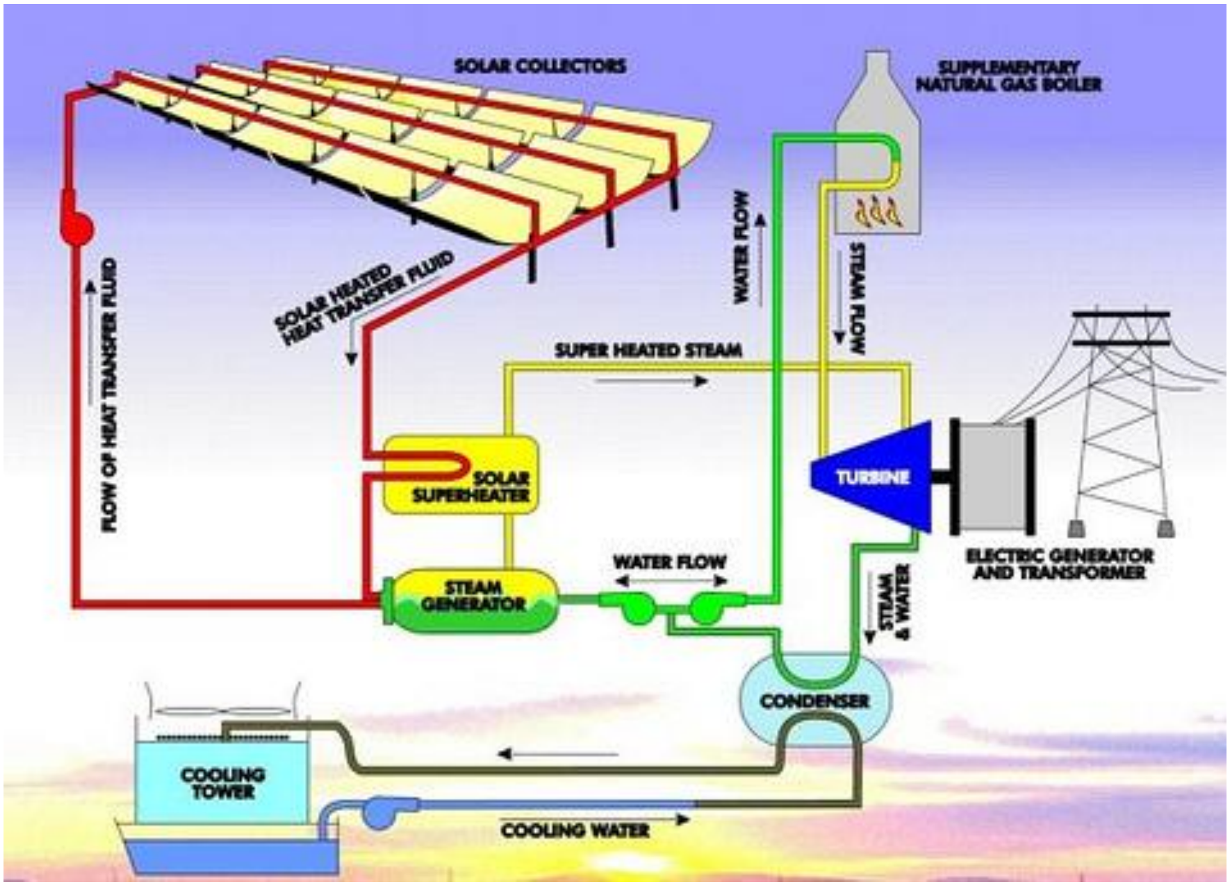


Exhibit 22 – a-Si photovoltaic cell composition[102]



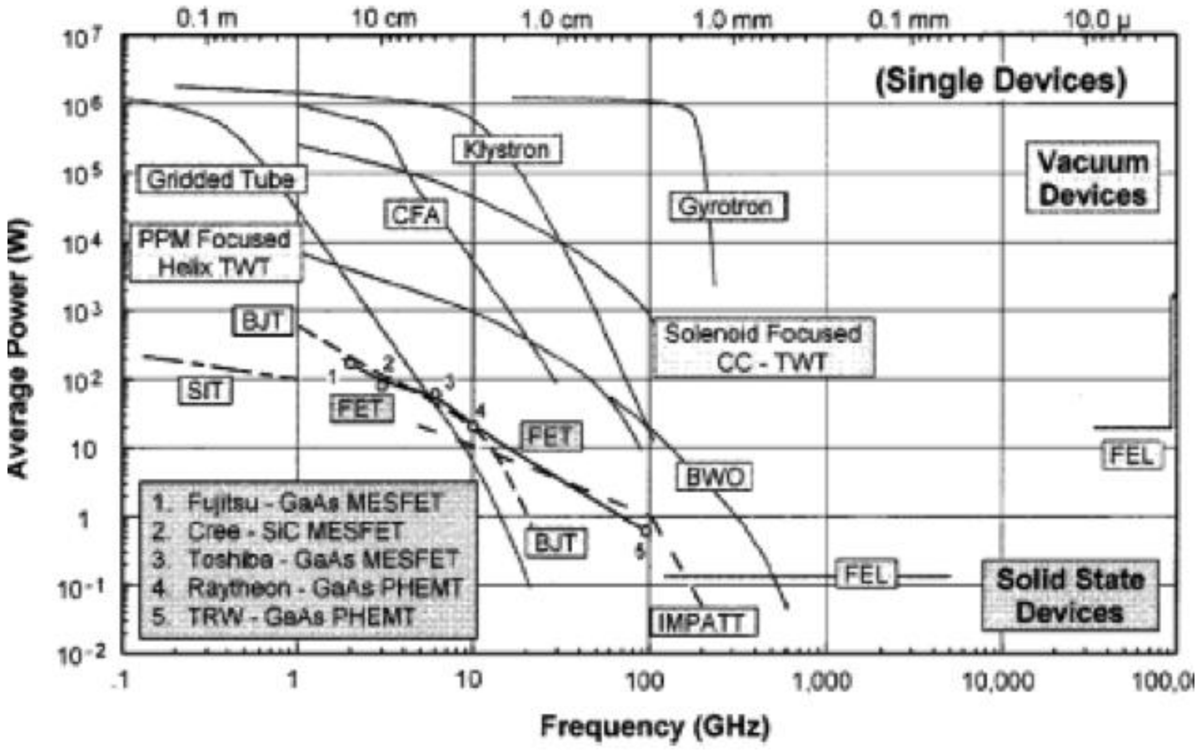
101. "Copper Indium Gallium Selenide Polycrystalline Thin Films." Absolute Astronomy Website, accessed November 17, 2010, http://image.absoluteastronomy.com/images/topicimages/c/co/copper_indium_gallium_selenide.gif.
102. "Amorphous Silicon Photovoltaic Cell Composition." U.S. DOE Energy Efficiency and Renewable Energy Website, accessed November 17, 2010, http://www.eere.energy.gov/basics/renewable_energy/images/illust_nip_structure.gif.

Exhibit 23 – Diagram of a solar dynamic system with water as the working fluid[103]



103. "Solar Dynamic System." Flickr Website, accessed November 17, 2010, http://farm3.static.flickr.com/2197/2366694264_f34caec302.jpg.

Exhibit 24 – Average RF output power versus frequency for various electronic devices and semiconductor systems[104].



104. Shinohara, Wireless Power.

Exhibit 25 – Typical parameters of the transmitting antenna of a SPS[105].

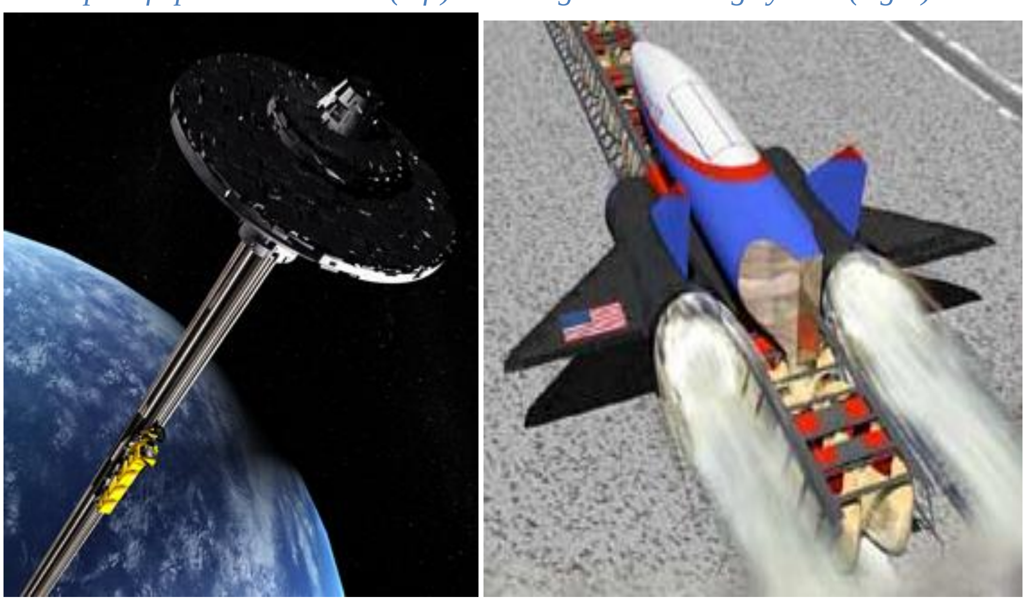
Model	Old JAXA model	JAXA1 model	JAXA2 Model	NASA/DOE model
Frequency	5.8 GHz	5.8 GHz	5.8 GHz	2.45 GHz
Diameter of transmitting antenna	2.6 kmϕ	1 kmϕ	1.93 kmϕ	1 kmϕ
Amplitude taper	10 dB Gaussian	10 dB Gaussian	10 dB Gaussian	10 dB Gaussian
Output power (beamed to earth)	1.3 GW	1.3 GW	1.3 GW	6.72 GW
Maximum power density at center	63 mW/ cm^2	420 mW/cm^2	114 mW/cm^2	2.2 W/ cm^2
Minimum power density at edge	6.3 mW/ cm^2	42 mW/ cm^2	11.4 mW/cm^2	0.22 W/ cm^2
Antenna spacing	0.75 λ	0.75 λ	0.75 λ	0.75 λ
Power per one antenna (Number of elements)	Max. 0.95 W (3.54 billion)	Max. 6.1W (540 million)	Max. 1.7 W (1,950 million)	Max. 185 W (97 million)
Rectenna Diameter	2.0 kmϕ	3.4 kmϕ	2.45 kmϕ	1 kmϕ
Maximum Power Density	180 mW/cm^2	26 mW/cm^2	100 mW/cm2	23 mW/cm^2
Collection Efficiency	96.5 %	86 %	87 %	89 %

Exhibit 26 – Concept demonstration of laser power beaming[106]

105. Shinohara, Wireless Power.
106. "Concept Demonstration of Laser Power Beaming." Lawrence Livermore National Laboratory, accessed November 17, 2010, https://lasers.llnl.gov/multimedia/publications/images/solar.jpg.

Exhibit 27 – Examples of Vertical Takeoff and Horizontal Landing (left)[107]*, Horizontal Takeoff and Landing (middle)*[108]*, and Vertical Takeoff and Landing (right)*[109]*.*

Exhibit 28 – Concepts of space elevator[110] *(left) and Maglev launching system (right)*[111]



107. "Vertical Take-Off and Horizontal Landing Launch Vehicle." Wikipedia, accessed November 17, 2010, http://en.wikipedia.org/wiki/File:Buran.jpg#filelinks.
108. "XCOR Aerospace EZ-Rocket." Wikipedia, accessed March 27, 2011, http://en.wikipedia.org/wiki/File:Xcor-ezrocket-N132EZ-020627-02.jpg.
109. "McDonnell Douglas DC-XA." Wikipedia, accessed March 27, 2011, http://en.wikipedia.org/wiki/File:McDonnell_Douglas_DC-XA.jpg.
110. "Space Elevator." Cosmos Magazine Website, accessed November 17, 2010, http://www.cosmosmagazine.com/files/imagecache/feature/files/features/print/20081216_space_elevator.jpg.
111. "Maglev Launching System." G2mil Website, accessed November 17, 2010, http://www.g2mil.com/maglev.jpg.

Exhibit 29 – Assumptions adopted for the initial financial viability analysis of SPS systems

Solar Power Satellite - Assumptions

Technical Assumptions affecting revenues		Cost Assumptions		
Grid conversion efficiency (2)	90%	Total Development Cost, \$M (2)	\$	8,000
Rectenna efficiency (2)	90%	Total Cost of SPS, \$M (2)	\$	5,044
Transmission efficiency (2)	96%	Total Cost of Rectenna, \$M (2)	\$	7,243
Power purchased from SPS	***100%***	Launch Cost to GEO, \$/kg (2)	\$	400
Power availability year-round	***100%***	LEO delivery cost, \$/kg (2)	\$	110
Power Generation Capacity, MW (2)	11,433	Maintenance cost, \$/KWh (2)	\$	0.0200
Lifetime, years (3)	40	***Maintenance cost growth, %/year***		***0%***
Degradation / year (3)	2.50%	30-year Capital cost, \$/KWh (2)	\$	0.0093
Technical Assumptions affecting costs		**Price Assumptions**		
Upper stage prop mass, kg (2)	31,396,520	Power price, \$/KWh (1)	\$	0.1151
Total SPS mass to be launched, kg (2)	54,331,613	***Power price growth, %/year***		***0%***

(1) Residential retail price, 2009. Source: U.S. Energy Information Administration - http://www.eia.doe.gov/cneaf/electricity/epa/epat7p4.html

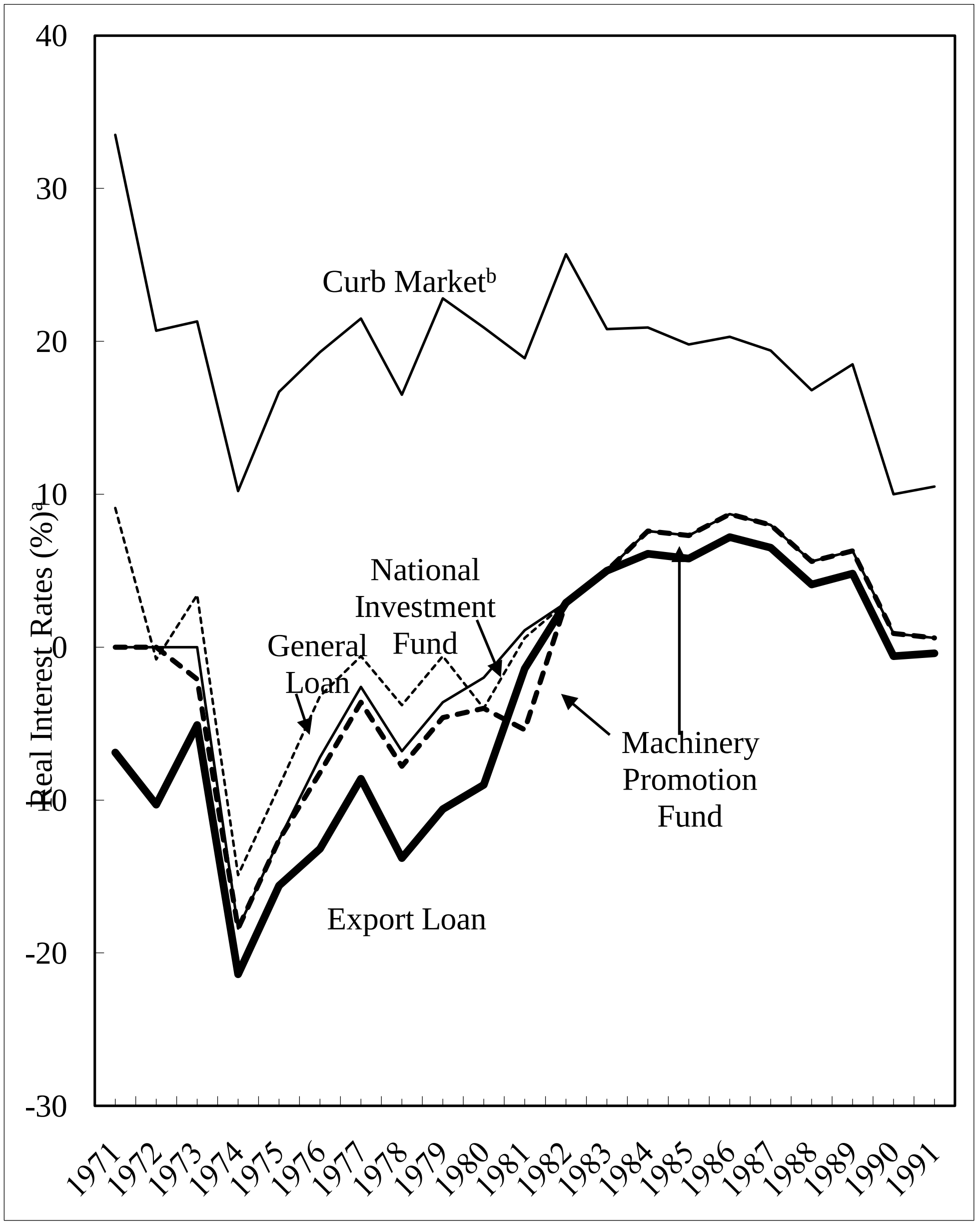
(2) Commercial Space Transportation Study - Chapter 3.8.2.2.2.3.3. Boeing, 2007. http://www.hq.nasa.gov/webaccess/CommSpaceTrans/

(3) Mankins, John C. A Fresh Look at Space Solar Power: New Architectures, Concepts and Technologies. Vol. IAF-97R.2.03, 1997

Exhibit 30 – Financial Model for the base-case model with assumptions presented in Exhibit 29

Figures in US$ M, unless otherwise indicated	**2011** **0**	**2012** **1**	**2013** **2**	**2014** **3**	**2015** **4**	**2016** **5**	**2017** **6**	**2018** **7**	**2019** **8**	**2020** **9**	**2021** **10**
Power Generation Capacity											
Installed Capacity, MW	-	11,433	11,147	10,861	10,575	10,290	10,004	9,718	9,432	9,146	8,860
Cumulative Degradation	*0.0%*	*0.0%*	*2.5%*	*5.0%*	*7.5%*	*10.0%*	*12.5%*	*15.0%*	*17.5%*	*20.0%*	*22.5%*
Annual Capacity, MWh	-	100,152,029	97,648,228	95,144,427	92,640,627	90,136,826	87,633,025	85,129,224	82,625,424	80,121,623	77,617,822
Power Installation Costs, $M											
a. Total Development cost	(8,000)										
b. Launch Cost	(40,268)										
c. SPS + Rectenna Cost	(12,287)										
x. Government Subsidies											
Salvage Value											
Depreciation		307	307	307	307	307	307	307	307	307	307
d. Depreciation Tax Shield	-	108	108	108	108	108	108	108	108	108	108
Operations											
Revenues from power		8,964	8,740	8,516	8,291	8,067	7,843	7,619	7,395	7,171	6,947
Power Supply consumed		100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Price per KWh, $		0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Annual price increase per KWh		*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*
Cost of Power Generation		(2,003)	(1,953)	(1,903)	(1,853)	(1,803)	(1,753)	(1,703)	(1,653)	(1,602)	(1,552)
Maintenance cost per KWh, $		0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Annual cost increase per KWh		*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*
Capital cost 30-yr amort.		(931)	(908)	(885)	(862)	(838)	(815)	(792)	(768)	(745)	(722)
30-yr Capital Cost, $/KWh		0.0093	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093
e. **Before Tax Operating Profit**	**-**	**6,029**	**5,879**	**5,728**	**5,577**	**5,426**	**5,276**	**5,125**	**4,974**	**4,823**	**4,673**
f. Tax Expense	-	(2,110)	(2,058)	(2,005)	(1,952)	(1,899)	(1,846)	(1,794)	(1,741)	(1,688)	(1,635)
After Tax Cash Flows (a+b+c+d+e+f)	**(60,555)**	**4,027**	**3,929**	**3,831**	**3,733**	**3,635**	**3,537**	**3,439**	**3,341**	**3,243**	**3,145**
Terminal Value											**32,275**
Discount Factor	*1.00*	*1.07*	*1.14*	*1.23*	*1.31*	*1.40*	*1.50*	*1.61*	*1.72*	*1.84*	*1.97*
NPV of Cash Flows	**(60,555)**	**3,763**	**3,431**	**3,127**	**2,848**	**2,591**	**2,357**	**2,141**	**1,944**	**1,764**	**1,599**
NPV of Terminal Value											**16,407**
Total NPV	**(60,555)**	**3,763**	**3,431**	**3,127**	**2,848**	**2,591**	**2,357**	**2,141**	**1,944**	**1,764**	**18,006**
NPV of SPS	**(21,802)**		**IRR of SPS**		**-4.1%**						

Exhibit 31 – South Korean real interest rates 1971-1991[112, 113]



Notes: [a] Real (i.e., inflation-adjusted) interest rates were calculated by substracting the GNP deflator rate from a nominal loan rate.

[b] The curb market rate is the informal rate at which small savers lend money to commercial and business borrowers.

112. Fields, Karl J. 1995. Enterprise and the State in Korea and Taiwan. Ithaca, New York: Cornell University Press.
113. Woo, Jung-En. 1991. Race to the Swift: State and Finance in Korean Industrialization. New York, New York: Columbia University Press.

Exhibit 32 – Sensitivity Analysis: Real Discount Rate and Corporate Tax Rate

in US$ M		Discount Rate									
NPV	**(21,802)**	9%	7%	5%	3%	1%	-1%	-3%	-5%	-7%	-9%
Corporate Tax Rate	35%	(27,567)	(21,802)	(13,968)	(2,957)	13,106	37,517	76,256	140,575	252,385	455,876
	30%	(25,283)	(19,134)	(10,786)	934	18,013	43,927	84,984	153,026	271,074	485,475
	25%	(22,999)	(16,467)	(7,605)	4,826	22,919	50,337	93,712	165,476	289,762	515,073
	20%	(20,715)	(13,799)	(4,423)	8,718	27,825	56,747	102,440	177,927	308,451	544,672
	15%	(18,431)	(11,132)	(1,242)	12,609	32,732	63,157	111,168	190,378	327,139	574,271
	10%	(16,147)	(8,464)	1,940	16,501	37,638	69,568	119,896	202,828	345,827	603,869
	5%	(13,863)	(5,797)	5,121	20,392	42,544	75,978	128,624	215,279	364,516	633,468
	0%	(11,579)	(3,129)	8,303	24,284	47,450	82,388	137,352	227,729	383,204	663,067

Exhibit 33 – Sensitivity Analysis: Retail Price of Electricity and Transportation Cost to GEO

in US$ M	Retail Price of Electricity ($/KWh)									
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
NPV (21,802)	$ 0.1151	$ 0.1675	$ 0.1921	$ 0.2649	$ 0.3147	$ 0.3607	$ 0.4181	$ 0.6534	$ 0.9200	$ 1.1600
Launch to GEO ($/kg) $ 4,872	$ (405,161)	$ (379,873)	$ (368,046)	$ (332,937)	$ (308,933)	$ (286,726)	$ (259,074)	$ (145,629)	$ (17,092)	$ 98,620
$ 4,000	$ (330,423)	$ (305,136)	$ (293,309)	$ (258,200)	$ (234,195)	$ (211,989)	$ (184,337)	$ (70,891)	$ 57,645	$ 173,357
$ 2,000	$ (158,967)	$ (133,680)	$ (121,852)	$ (86,743)	$ (62,739)	$ (40,533)	$ (12,881)	$ 100,565	$ 229,102	$ 344,813
$ 1,000	$ (73,239)	$ (47,952)	$ (36,124)	$ (1,015)	$ 22,989	$ 45,195	$ 72,847	$ 186,293	$ 314,830	$ 430,542
$ 800	$ (56,093)	$ (30,806)	$ (18,979)	$ 16,130	$ 40,135	$ 62,341	$ 89,993	$ 203,439	$ 331,975	$ 447,687
$ 600	$ (38,948)	$ (13,660)	$ (1,833)	$ 33,276	$ 57,280	$ 79,487	$ 107,139	$ 220,584	$ 349,121	$ 464,833
$ 400	$ (21,802)	$ 3,485	$ 15,313	$ 50,422	$ 74,426	$ 96,632	$ 124,284	$ 237,730	$ 366,267	$ 481,978
$ 200	$ (4,656)	$ 20,631	$ 32,458	$ 67,567	$ 91,572	$ 113,778	$ 141,430	$ 254,876	$ 383,412	$ 499,124

(1) U.S.residential average retail price per kilowatthour. Source: EIA - http://www.eia.doe.gov/cneaf/electricity/epa/fig7p5.html

(2) Electricity cost in France. Europe's Energy Portal - http://www.energy.eu

(3) U.S. retail price per KWh in selected states (NY, CT, MA, AK, and HI). Source: EIA - http://www.eia.doe.gov/cneaf/electricity/epa/fig7p5.html

(4) Electricity cost in the Netherlands. Maritime Electric: http://www.maritimeelectric.com/understanding_electricity/el_comparing_prices.asp

(5) Electricity cost in Germany. Europe's Energy Portal - http://www.energy.eu

(6) Electricity cost in Italy. Europe's Energy Portal - IBID

(7) Electricity cost in Denmark. Maritime Electric: http://www.maritimeelectric.com/understanding_electricity/el_comparing_prices.asp

(8) Electricity cost in Kugluktuk, Nunavut. Maritime Electric: IBID

(9) Electricity cost for US military in Iraq. Charania, A.C. et al, "A rational roadmap for developing a first revenue space solar power satellite". IAC, 2010.

(10) Electricity cost for US military in Afghanistan. IBID

Exhibit 34 – Sensitivity Analysis: Growth of Retail Price of Electricity and SPS Lifespan

in US$ M		Growth of Retail Price of Electricity (% p.a.)							
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
NPV	**(21,802)**	0%	2%	4%	6%	8%	10%	12%	18%
Lifetime of SPS (years)	40	$ (21,802)	$ (11,433)	$ 2,566	$ 21,896	$ 49,188	$ 88,544	$ 146,421	$ 567,352
	45	$ (20,200)	$ (8,435)	$ 7,940	$ 31,403	$ 66,009	$ 118,482	$ 200,105	$ 888,206
	50	$ (18,837)	$ (5,769)	$ 12,948	$ 40,743	$ 83,554	$ 151,846	$ 264,350	$ 1,371,675
	60	$ (16,663)	$ (1,270)	$ 21,951	$ 58,865	$ 120,804	$ 230,321	$ 433,430	$ 3,216,402
	70	$ (15,024)	$ 2,339	$ 29,750	$ 76,187	$ 160,960	$ 327,455	$ 676,732	$ 7,518,386
	80	$ (13,757)	$ 5,265	$ 36,512	$ 92,685	$ 204,116	$ 447,737	$ 1,028,537	$ 17,692,595
	90	$ (12,754)	$ 7,665	$ 42,386	$ 108,363	$ 250,415	$ 596,899	$ 1,539,824	$ 42,037,223
	100	$ (11,943)	$ 9,654	$ 47,505	$ 123,241	$ 300,036	$ 782,227	$ 2,286,573	$ 100,858,725

(1) Current assumption - prices are stable forever.

(2) Prices double every 36 years.

(3) Prices double every 18 years.

(4) Prices double every 12 years.

(5) Prices double every 9 years.

(6) Prices double every 7 years.

(7) Prices double every 6 years.

(8) Prices double every 4 years.

Exhibit 35 – Sensitivity Analysis: Growth of Retail Price of Electricity and Transportation Costs to GEO

in US$ M			Growth of Retail Price of Electricity (% p.a.)					
			(1)	(2)	(3)	(4)	(5)	(6)
NPV		**(21,802)**	6%	8%	10%	12%	14%	18%
Launch to GEO ($/kg)	(a)	$ 14,295	$ (1,169,296)	$ (1,142,005)	$ (1,095,704)	$ (1,044,772)	$ (936,087)	$ (623,840)
	(b)	$ 11,966	$ (969,619)	$ (942,328)	$ (896,027)	$ (845,095)	$ (736,410)	$ (424,163)
	(c)	$ 4,872	$ (361,463)	$ (334,171)	$ (287,870)	$ (236,938)	$ (128,253)	$ 183,994
		$ 3,000	$ (200,997)	$ (173,705)	$ (127,404)	$ (76,473)	$ 32,213	$ 344,459
		$ 1,500	$ (72,405)	$ (45,113)	$ 1,188	$ 52,120	$ 160,805	$ 473,051
		$ 800	$ (12,395)	$ 14,896	$ 61,198	$ 112,129	$ 220,815	$ 533,061
		$ 400	$ 21,896	$ 49,188	$ 95,489	$ 146,421	$ 255,106	$ 567,352
		$ 200	$ 39,042	$ 66,333	$ 112,634	$ 163,566	$ 272,251	$ 584,498

(a) Delta IV. http://www.astronautix.com/lvs/deltaiv.htm

(b) SpaceX Falcon9. http://www.spacex.com/falcon9.php#pricing_and_performance.

(c) SpaceX Falcon9-Heavy. http://www.spacex.com/falcon9_heavy.php#pricing_and_performance

(1) Prices double every 12 years.

(2) Prices double every 9 years.

(3) Prices double every 7 years.

(4) Prices double every 6 years.

(5) Prices double every 5 years.

(6) Prices double every 4 years.

Exhibit 36 – Set of assumptions chosen for the high probability outcome

Solar Power Satellite - Assumptions

Technical Assumptions affecting revenues	
Grid conversion efficiency (2)	90%
Rectenna efficiency (2)	90%
Transmission efficiency (2)	96%
Power purchased from SPS	***100%***
Power availability year-round	***100%***
Power Generation Capacity, MW (2)	11,433
Lifetime, years (3)	50
Degradation / year (3)	2.00%

Technical Assumptions affecting costs	
Upper stage prop mass, kg (2)	31,396,520
Total SPS mass to be launched, kg (2)	54,331,613

Cost Assumptions		
Total Development Cost, $M (2)	$	8,000
Total Cost of SPS, $M (2)	$	5,044
Total Cost of Rectenna, $M (2)	$	7,243
Launch Cost to GEO, $/kg (2)	$	3,898
LEO delivery cost, $/kg (2)	$	110
Maintenance cost, $/KWh(2)	$	0.0200
Maintenance cost growth, %/year		***0%***
30-year Capital cost, $/KWh(2)	$	0.0093

Price Assumptions		
Power price, $/KWh(1)	$	0.1921
Power price growth, %/year		***4%***

(1) Residential retail price, 2009 for NY, MA, CT, AK, and HI. EIA - http://www.eia.doe.gov/cneaf/electricity/epa/epat7p4.html

(2) Commercial Space Transportation Study - Chapter 3.8.2.2.2.3.3. Boeing, 2007. http://www.hq.nasa.gov/webaccess/CommSpaceTrans/

(3) Lifespan 25% higher than the one suggested by Mankins, John C. "*A Fresh Look*"

(4) SpaceX Falcon9-Heavy. http://www.spacex.com/falcon9_heavy.php#pricing_and_performance

Exhibit 37 – Financial model output for the high probability outcome

Figures in US$ M, unless otherwise indicated	2011 0	2012 1	2013 2	2014 3	2015 4	2016 5	2017 6	2018 7	2019 8	2020 9	2021 10
Power Generation Capacity											
Installed Capacity, MW	-	11,433	11,204	10,976	10,747	10,518	10,290	10,061	9,832	9,604	9,375
Cumulative Degradation	*0.0%*	*0.0%*	*2.0%*	*4.0%*	*6.0%*	*8.0%*	*10.0%*	*12.0%*	*14.0%*	*16.0%*	*18.0%*
Annual Capacity, MWh	-	100,152,029	98,148,988	96,145,948	94,142,907	92,139,866	90,136,826	88,133,785	86,130,745	84,127,704	82,124,664
Power Installation Costs, $M											
a. Total Development cost	(8,000)										
b. Launch Cost	(340,110)										
c. SPS + Rectenna Cost	(12,287)										
x. Government Subsidies											
Salvage Value											
Depreciation		246	246	246	246	246	246	246	246	246	246
d. Depreciation Tax Shield	-	17	17	17	17	17	17	17	17	17	17
Operations											
Revenues from power		14,960	15,248	15,534	15,819	16,101	16,381	16,658	16,931	17,198	17,461
Power Supply consumed		100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Price per KWh, $		0.19	0.20	0.21	0.22	0.22	0.23	0.24	0.25	0.26	0.27
Annual price increase per KWh		*4.0%*	*4.0%*	*4.0%*	*4.0%*	*4.0%*	*4.0%*	*4.0%*	*4.0%*	*4.0%*	*4.0%*
Cost of Power Generation		(2,003)	(1,963)	(1,923)	(1,883)	(1,843)	(1,803)	(1,763)	(1,723)	(1,683)	(1,642)
Maintenance cost per KWh, $		0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Annual cost increase per KWh		*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*	*0.0%*
Capital cost 30-yr amort.		(931)	(913)	(894)	(876)	(857)	(838)	(820)	(801)	(782)	(764)
30-yr Capital Cost, $/KWh		0.0093	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093
e. **Before Tax Operating Profit**	**-**	**12,026**	**12,372**	**12,717**	**13,060**	**13,402**	**13,740**	**14,076**	**14,407**	**14,734**	**15,054**
f. Tax Expense	-	(842)	(866)	(890)	(914)	(938)	(962)	(985)	(1,008)	(1,031)	(1,054)
After Tax Cash Flows (a+b+c+d+e+f)	**(360,397)**	**11,201**	**11,523**	**11,844**	**12,163**	**12,481**	**12,796**	**13,108**	**13,416**	**13,719**	**14,018**
Terminal Value											**285,961**
Discount Factor	*1.00*	*1.03*	*1.06*	*1.09*	*1.13*	*1.16*	*1.19*	*1.23*	*1.27*	*1.30*	*1.34*
NPV of Cash Flows	**(360,397)**	**10,875**	**10,862**	**10,839**	**10,807**	**10,766**	**10,716**	**10,658**	**10,591**	**10,515**	**10,430**
NPV of Terminal Value											**212,782**
Total NPV	**(360,397)**	**10,875**	**10,862**	**10,839**	**10,807**	**10,766**	**10,716**	**10,658**	**10,591**	**10,515**	**223,212**
NPV of SPS	**1,950**		**IRR of SPS**		**0.03%**						

Exhibit 38 – Set of assumptions chosen for the medium probability outcome

Solar Power Satellite - Assumptions

Technical Assumptions affecting revenues		**Cost Assumptions**		
Grid conversion efficiency (2)	90%	Total Development Cost, $M (2)	$	8,000
Rectenna efficiency (2)	90%	Total Cost of SPS, $M (2)	$	5,044
Transmission efficiency (2)	96%	Total Cost of Rectenna, $M (2)	$	7,243
Power purchased from SPS	***100%***	Launch Cost to GEO, $/kg (2)	$	800
Power availability year-round	***100%***	LEO delivery cost, $/kg (2)	$	110
Power Generation Capacity, MW (2)	11,433	Maintenance cost, $/KWh (2)	$	0.0200
Lifetime, years (3)	50	***Maintenance cost growth, %/year***		***2%***
Degradation / year (3)	2.00%	30-year Capital cost, $/KWh (2)	$	0.0093
Technical Assumptions affecting costs		**Price Assumptions**		
Upper stage prop mass, kg (2)	31,396,520	Power price, $/KWh (1)	$	0.1921
Total SPS mass to be launched, kg (2)	54,331,613	***Power price growth, %/year***		***2%***

(1) Residential retail price, 2009 for NY, MA, CT, AK, and HI. EIA - http://www.eia.doe.gov/cneaf/electricity/epa/epat7p4.html

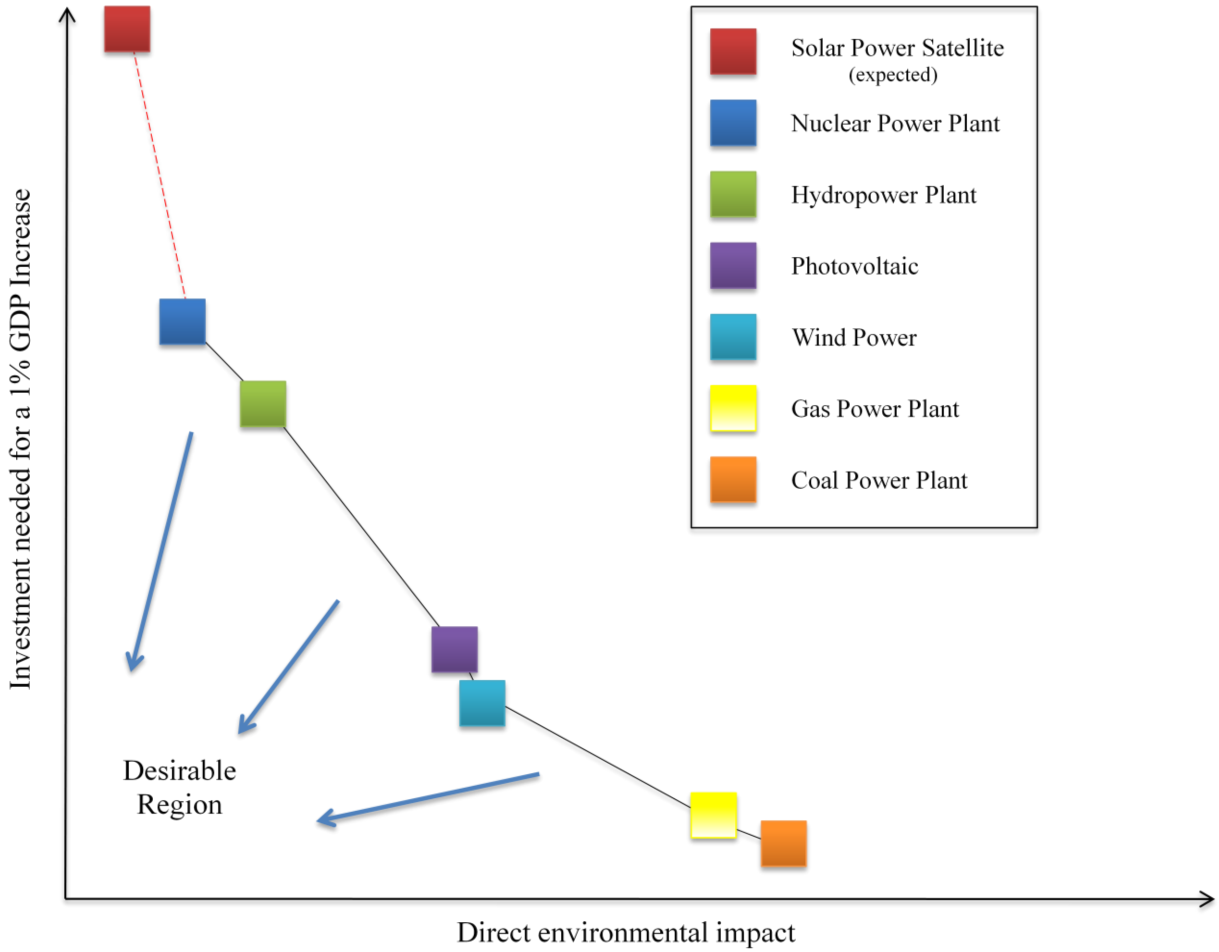
(2) Commercial Space Transportation Study - Chapter 3.8.2.2.2.3.3. Boeing, 2007. http://www.hq.nasa.gov/webaccess/CommSpaceTrans/

(3) Lifespan 25% higher than the one suggested by Mankins, John C. "*A Fresh Look*"

Exhibit 39 – Financial model output for the medium probability outcome

Figures in US$ M, unless otherwise indicated	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
	0	1	2	3	4	5	6	7	8	9	10
Power Generation Capacity											
Installed Capacity, MW	-	11,433	11,204	10,976	10,747	10,518	10,290	10,061	9,832	9,604	9,375
Cumulative Degradation	*0.0%*	*0.0%*	*2.0%*	*4.0%*	*6.0%*	*8.0%*	*10.0%*	*12.0%*	*14.0%*	*16.0%*	*18.0%*
Annual Capacity, MWh	-	100,152,029	98,148,988	96,145,948	94,142,907	92,139,866	90,136,826	88,133,785	86,130,745	84,127,704	82,124,664
Power Installation Costs, $M											
a. Total Development cost	(8,000)										
b. Launch Cost	(74,559)										
c. SPS + Rectenna Cost	(12,287)										
x. Government Subsidies	-										
Salvage Value											
Depreciation		246	246	246	246	246	246	246	246	246	246
d. Depreciation Tax Shield	-	49	49	49	49	49	49	49	49	49	49
Operations											
Revenues from power		14,960	14,954	14,942	14,924	14,898	14,866	14,826	14,779	14,724	14,661
Power Supply consumed		100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Price per KWh, $		0.19	0.20	0.20	0.20	0.21	0.21	0.22	0.22	0.23	0.23
Annual price increase per KWh		*2.0%*	*2.0%*	*2.0%*	*2.0%*	*2.0%*	*2.0%*	*2.0%*	*2.0%*	*2.0%*	*2.0%*
Cost of Power Generation		(2,003)	(2,002)	(2,001)	(1,998)	(1,995)	(1,990)	(1,985)	(1,979)	(1,971)	(1,963)
Maintenance cost per KWh, $		0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Annual cost increase per KWh		*2.0%*	*2.0%*	*2.0%*	*2.0%*	*2.0%*	*2.0%*	*2.0%*	*2.0%*	*2.0%*	*2.0%*
Capital cost 30-yr amort.		(931)	(913)	(894)	(876)	(857)	(838)	(820)	(801)	(782)	(764)
30-yr Capital Cost, $/KWh		0.0093	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093
e. **Before Tax Operating Profit**	**-**	**12,026**	**12,039**	**12,047**	**12,050**	**12,047**	**12,037**	**12,021**	**11,999**	**11,970**	**11,934**
f. Tax Expense	-	(2,405)	(2,408)	(2,409)	(2,410)	(2,409)	(2,407)	(2,404)	(2,400)	(2,394)	(2,387)
After Tax Cash Flows (a+b+c+d+e+f)	**(94,846)**	**9,670**	**9,681**	**9,687**	**9,689**	**9,686**	**9,679**	**9,666**	**9,648**	**9,625**	**9,596**
Terminal Value											**106,627**
Discount Factor	*1.00*	*1.07*	*1.14*	*1.23*	*1.31*	*1.40*	*1.50*	*1.61*	*1.72*	*1.84*	*1.97*
NPV of Cash Flows	**(94,846)**	**9,037**	**8,455**	**7,908**	**7,392**	**6,906**	**6,449**	**6,020**	**5,616**	**5,236**	**4,878**
NPV of Terminal Value											**54,204**
Total NPV	**(94,846)**	**9,037**	**8,455**	**7,908**	**7,392**	**6,906**	**6,449**	**6,020**	**5,616**	**5,236**	**59,082**
NPV of SPS (incl. TV)	**27,255**		**IRR of SPS (incl. TV)**		**3.7%**						

Exhibit 40 – Conceptual Pareto Frontier for currently existing energy sources.



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