21st Century Trends in Space-Based Solar Power Generation and Storage

Report submitted for NASA Research Announcement: NNA15ZBP0001N-B1, Economic Research for Space Development

Nick Proctor, Rod Eggert, Ian Lange, Angel Abbud Madrid, and Peter Maniloff

Colorado School of Mines

Project number: NNX 80NSSC17K0327

Table of Contents

Abstract

The market for space solar power (SSP) has taken many twists and turns in the last 10 years. This analysis utilizes a case study of SSP for remote mine operations to determine its economic feasibility. This case study is chosen because remote mines may offer a good business case – they consume large quantities of electricity for large timespans but rely on expensive sources for fuel. If SSP is found to be cost competitive with petroleum fuels used for minesite electricity production and can provide a return on investment in remote regions, a market could exist for SSP that would be attractive to investors and independent power producers (IPPs). Our project evaluates the feasibility of using SSP to meet near-term commercial energy demand for mining and resource extraction on Earth from the perspective of an IPP. Our evaluation develops estimates of a discounted cash flow (DCF) evaluation and then assesses the sensitivity of the DCF model to changes in its underlying assumptions. The results indicate that for SSP to be considered a viable power alternative for niche power markets, such as remote mining operations, the assumed manufacturing and transportation costs must decrease by an order of magnitude. However, promise is shown by using a larger system to feed multiple mines at the same time.

Executive Summary

Space solar power (SSP) is a renewable energy technology that has been studied for five decades. The concept could provide round-the-clock clean energy to the world's largest population centers, improving Earth's atmosphere by reducing emissions from conventional power sources. Most SSP economic studies have focused on huge, base load scale applications. These studies have largely determined that the cost of power delivered from space cannot compete with power generated on Earth. Our economic viability study focuses on the niche power market of remote mining operations, as mines typically utilize diesel to generate power, and consequently pay a higher rate per kilowatt hour than most grid-tied power consumers, by a factor of ten. We examine power demand and costs at remote mines and incorporate these parameters with John Mankins' proposed SPS-ALPHA 18 MW system, and several Earth-to-orbit transport systems to determine a combination of factors that demonstrate the best business case for SSP's feasibility. Several business scenarios are also considered to determine mining applications where SSP might demonstrate economic viability. Economic feasibility is determined by employing a DCF evaluation of the costs and revenues associated with operating an SSP system, with net present value (NPV) and internal rate of return (IRR) metrics informing the investment decision.

Several remote mines have reduced consumption of electricity from fossil fuel power generation, and have hybridized their operations by purchasing renewable power from independent power producers (IPP) who install power plants near remote mines. A case study of a specific mine in the Northwest Territories of Canada is discussed to provide background for the DCF analysis.   This arrangement is a growing trend in the industry as it has proven beneficial for the mine in reducing carbon emissions, and has decreased operating expenses as a hedge against fuel price volatility.

Deploying SPS-ALPHA to geosynchronous orbit (GEO) with SpaceX's forthcoming Big Falcon Rocket (BFR) transportation technology yields the best business case for SSP in remote mining operations, with a total cost of approximately $2 billion. With this promising cost estimate, the NPV of the cash flows is -$1.4 billion, and the IRR is -4.96%. As NPV must be greater than $0.00 to be considered economically feasible, SSP is not an economically viable energy source for remote mining operations, under our given assumptions.

Breakeven analysis shows that total costs must equal $281.5 million, a 94% reduction from Mankins' estimated cost to first power of $4.5 billion. This can be achieved as technological breakthroughs in transport systems are achieved. GEO transport costs per kilogram must decrease from Mankins' assumed $3,000 to $188. Alternatively, as breakthroughs in materials and platform production are achieved, system mass needs to fall from Mankins' estimate of 1,043,968 kilograms to 65,315 kilograms to breakeven. One promising scenario is for a larger system to power multiple mines at the same time. Larger systems cost of producing electricity does not proportionately increase with size, however the revenues do, making this scenario potentially attractive to governments or as demonstration projects.

Incorporation of other SSP technologies, business arrangements, and financing arrangements should still be explored to determine viability. We recommend periodic economic evaluation into SSP for remote mining operations as breakthroughs in manufacturing and launch technologies are achieved as well as exploration of other plausible business cases – large electricity consumers facing expensive energy sources.

I. Introduction

First conceived over 75 years ago, space solar power (SSP) has been studied, patented, championed, dismissed and reevaluated as a possible answer to providing global energy security. While the concept of a satellite wirelessly beaming power to earth is generally considered technically feasible, its economic feasibility is viewed as problematic. If proven economically feasible, however, SSP could play a sizeable role in the generation of alternative energy.

Most existing SSP feasibility studies have focused on baseload applications, which requires technology that is extremely massive, and therefore, cost prohibitive. By contrast, little research has been performed on the economic feasibility of smaller scale SSP technology designed for specific markets. Niche energy markets, accustomed to paying a higher rate per kilowatt hour (kWh), such as remote mining operations, represent potential for the testing of a small scale SSP system and could initiate in the evolution of a system capable of providing energy to the masses.

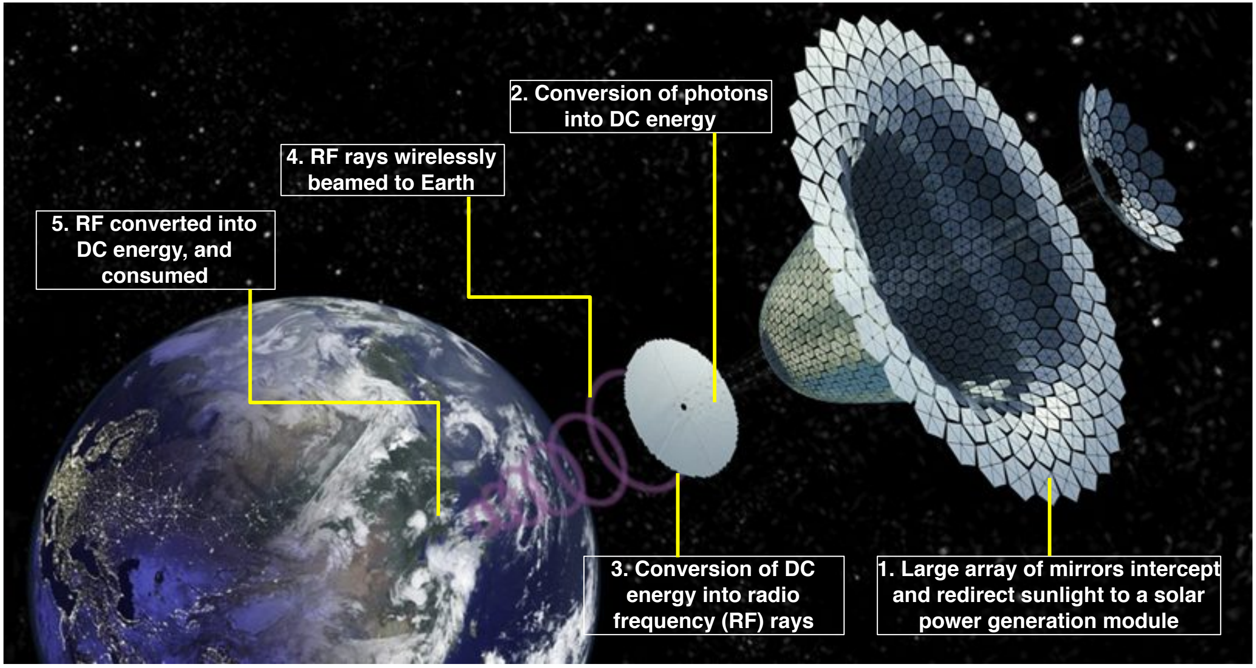
Former director of the National Space Society, Al Globus reasons in his 2011 paper *Towards an Early Profitable PowerSat, Part II* “If a small, relatively inexpensive, SSP PowerSat for niche markets can be profitable, then experience will be gained, more PowerSats will be built, and the launch rate will increase; all of which will drive down costs and widen the markets in which SSP can compete. Eventually, of course, we would like to see very large PowerSats filling the same role of providing 24/7 power as nuclear, coal, oil, and natural gas are today. However, there is little likelihood of getting there in a single step. What we need is a small step in the right direction.”[i] The terrestrial solar and wind power industries provide salient examples of this strategy.

John Mankins refers to such markets as Commercial Premium Niche Power (C-PNP) markets. These markets “are entirely dependent on the specifics of the location and situation; however, they can occur in a wide variety of locations around the globe. The wholesale and retail prices for C-PNP power generated from whatever source can vary widely depending on the location, local power generating capacity, seasonal considerations and other market factors.”[ii] Remote mining operations may represent one such pilot market for SSP, and could be the first small step to which Al Globus refers.

What is Space Solar Power?

Space solar power (SSP) is a sustainable energy concept that presents many theoretical benefits to humankind. The most beneficial of its proposed utility includes delivering a never-ending supply of clean, renewable electricity to the terrestrial power grid. A highly-simplified description of a SSP system entails (1) a large satellite in geosynchronous orbit (GEO), consisting of mirrors which focus sunlight onto photovoltaic (PV) panels, (2) where photons are converted into DC energy. (3) The DC energy is then converted into radio frequency (RF), or microwave ray. (4) A wireless power transmitter then beams the RF ray to a rectifying antenna (“rectenna”) positioned on Earth’s surface. (5) The rectenna converts the RF beam into DC electricity, and is transmitted via wire to the local power grid for consumption. Figure 1 shows a diagram of the SSP concept. For a more detailed description of the system’s mechanics, please reference the works of John C. Mankins, particularly “*The Case for Space Solar Power*”.

Figure 1: Simplified diagram of space solar power concept



Source: Mankins, The Case for Space Solar Power

Ideal Market Conditions for SSP

While there may be an abundance of promise for SSP, it still must compete with other technologies that produce electricity. Unfortunately, the wholesale price of electricity has come down considerably over the last ten years.[iii] There are many reasons for the decline in terrestrial grid electricity price but the main one is the invention of hydraulic fracturing which has lowered natural gas prices by 65% since 2008.[iv] With most wholesale electricity markets trading electricity for around $30 per MWh ($0.03 per kWh), SSP is not remotely cost competitive in these markets.

As a result, this analysis looked for other potential markets for electricity where SSP might be competitive. In order to find these possible markets we set out three market conditions that would be ideal for SSP, and its investors, to compete with other sources of electricity. They are

1. Not connected to the terrestrial electricity grid
2. Consistent power demand throughout most of the day
3. Customers' interested in signing long term power purchase agreements (PPA)

These conditions set up an ideal market for SSP as they fit in well with SSP capabilities. A customer of electricity who is not connected to the electricity grid does not have access to $30 per MWh electricity discussed above. As such, SSP is generally competing with diesel that is trucked great distances or a stand-alone renewable technology. Both of these options will have prices many multiples of $30 per MWh. SSP can provide a consistent power supply throughout most hours and if that matches the customers profile then no additional storage or other technologies are needed. This keeps the cost of the SSP system lower and better able to compete with other options. Finally, investors prefer lower risk in their potential returns and PPAs are the main avenue for electricity producers to lock in their revenues. A customer who would sign a 10 year PPA for a given amount of electricity at a given price would provide a large amount of value for a potential SSP investor. These conditions led us to the remote mining industry as a likely niche market for SSP.

In recent years, mining companies have struggled with low commodity prices, which affects investment decisions in new projects. This environment also creates an opportunity for independent power providers (IPP) to help remote mines, who rely primarily on petroleum fuels to power their operations, hedge exposure to volatile petroleum prices. Mining firms understand the need to base their development plans on long-term energy pricing, as their "mines need 24/7 power, delivered through a stable transmission infrastructure."[v] Fuel price volatility is hedged as mining firms enter into a power purchase agreement (PPA) with an IPP, agreeing to buy power from the IPP at a contracted price per kWh, for a contracted period of time.

Additionally, Warner Priest, Business Development Manager at Siemens shares his insight on the latest developments in renewable energy technologies in the Australian mining industry. "When it comes to mining, one of the major concerns is the life of the mine. The mine life issue seems to be prevalent within the gold mining sector. When it comes to other mining operations like magnetite, phosphate or rare earth metals, we are seeing mine lives of 20 to 75 years. When the mine life is that long, the business case for renewables absolutely makes sense. Generally, we find that that the business case stacks up well for mines with an expected life of ten years or more, depending on what renewable technologies can be deployed." [vi]

II. Renewables in Remote Mining Operations

Power Hybridization

The idea of utilizing renewable energy to power remote mines is not a foreign concept to mining companies. In fact, several mines have already hybridized their operations with renewable power systems. Miners have chosen to partially energize their operations with renewable power for various reasons, including decreasing operating expenses, reducing fuel volume consumption, hedging against petroleum price volatility, and reducing the firm's carbon footprint. Additionally, the surrounding communities benefit from the energy infrastructure after mine closure, with the option to source power needs from architecture.

Mining companies do not typically install the alternative power systems themselves. Rather, an independent power provider (IPP) is engaged by the mining company to determine the feasibility of installing a renewable energy system near the mine, with the mine being the IPP's long-term customer. If feasible, the IPP will build and operate the power system, and the IPP and the mine enter a power purchase agreement (PPA) for a contracted period, with a predetermined price per kWh. Table 1 shows specifics of a few hybridized remote mining operations.

Table 1: Examples of Renewable Energy Use at Mines

Company	Mine	Year Commissioned	Location	Power System	Installed Capacity	IPP's CAPEX	Carbon not emitted (tonnes/yr)
B2 Gold	Otjikoto	2018	Namibia	Solar	7 MW	$9 M	9,000
GMA Garnet	Australia Operation	2019 (planned)	Western Australia	Solar & Wind	3 MW	$8 M	5,000
IAMGOLD	Essakane	2018	Burkina Faso	Solar	15 MW	$20 M	17,000
Rio Tinto	Diavik	2012	Northwest Territories	Wind	9 MW	$33 M	14,000
Sandfire Resources	DeGrussa	2016	Western Australia	Solar	11 MW	$40 M	20,000

Source: Survey results of energy directors of various mining firms

Case Study: Fortune Minerals' NICO Project

Unique challenges affecting each mining venture makes SSP an energy concept worth consideration. Some mines are only able to receive fuel deliveries during winter months on ice roads, due to poor road infrastructure and incompetent ground. Others operate in jurisdictions where punitive carbon emission policies increase the cost burning petroleum fuels for power. Fortune Minerals has encountered difficulty in selecting an adequate power source for its NICO project.

NICO is a vertically integrated development project comprised of a planned mine and concentrator in Canada's Northwest Territories, and a refinery in Saskatchewan. As the global demand for lithium-ion batteries is projected to increase over the next decade, the NICO deposit has become strategically important to the supply chain of lithium-ion battery production, as cobalt is the mine's primary metal, with gold, bismuth, and copper as byproducts.

The mine site has a proposed installed capacity of 12.6 MW, requiring on-site power generation. The processing site in Saskatchewan has a proposed installed capacity of 12 MW, requiring no energy generation as it will be grid-connected. It is anticipated that NICO will have a mine life of 20 years, with production commencing in 2023. In consideration of generating power for the mine in the Northwest Territories, the ideal energy source was clear. Traditional and alternative energy sources each carry notable favorable and unfavorable issues. An explanation of each power option initially considered follows below.

Diesel: Costs $0.25 – $0.30 per kilowatt hour. This cost estimate is projected to increase due to the enactment of Canada's Carbon Pricing Policy, which went into effect in 2018. Carbon price will start at a minimum of $10 CAD per tonne in 2018, and rise by $10 CAD per year to $50 CAD per tonne in 2022 and beyond. With production expected to commence in 2023, NICO will experience only the highest rate of carbon tax penalty. It is estimated that these taxes will cost Fortune Minerals $3.2 million CAD per annum, resulting in an increased cost per kWh of roughly

15%. With the increase in operating costs due to carbon taxes, evaluation of other power generation methods is required.

Additionally, carbon taxes simultaneously boost the price that IPPs could charge mining customers per kWh, thus increasing revenues. An evaluation of SSP feasibility incorporating the impacts of carbon taxes increasing the costs associated with burning diesel is conducted and discussed below in the “Other Business Cases” section.

PV Solar: PV solar is most effective at locations between latitudes of 0° and 50°. With NICO positioned north of 60° latitude, the location is too extreme for solar to be a practical option.

Hydro: The project is only 22km from 4 hydro dams, but there is insufficient surplus power to accommodate the loads required by the mine. A nearby 14 MW run-of-river project was also assessed in a feasibility study, but no work has been done to advance the project through environmental base-line studies. Environmental assessment, permitting and construction would take a minimum of seven years to complete, rendering hydro power unavailable for NICO start-up timeframe.

Wind: The Diavik Diamond Mine north and east of NICO uses diesel generators in combination with a 9.2 MW wind farm. The wind power mitigates risk of diesel supply chain issues on winter ice roads, but is not cost competitive with diesel. Wind’s all-in-costs are greater than diesel, and does not allow for heat recovery to be used in buildings. Wind power is also subject to geographic constraints which arise from intermittency in weather and wind patterns.

Modular Nuclear Reactor: The concept of small scale nuclear reactors has existed for several decades. These reactors are envisioned to vary in size from a couple MW up to several hundred MW. However, there exist no permitted analogues, rendering the permitting risk for the NICO project unacceptable.

Liquefied Natural Gas (LNG): LNG is currently the best low-carbon emitting option for NICO, as it also allows for heat recapture for buildings. However, any supply disturbance could be unfavorable as gas dissipates after a month of storage, requiring additional costs to recompress the gas.

With the energy issues involved with the NICO project, SSP shows conceptual merit. The fact that SSP has no fuel storage requirements, requires less dependency on ice-roads, and would not lead to carbon tax payments all are strong points in its favor. Further, because SSP displays virtually no power intermittency, it could be a reliable option to power the entire operation, without hybridizing with a smaller diesel system.

While NICO presents several favorable circumstances for SSP, it is not a perfect example. Complications due to its high latitude create inefficiencies in directing the radio frequency (RF) beam from geosynchronous orbit to the surface of the Earth. Projects nearer the equator are more favorable for a single solar satellite in geosynchronous orbit, keeping costs to a minimum.

Rather than placing the power satellite in a geosynchronous orbit, a Molniya orbit may be favorable, considering the NICO's extreme latitude. However, a Molniya orbit could require multiple satellites to provide 24 hour coverage. Figure 2 shows a diagram of SSP configuration in Molniya orbit. If placed in geosynchronous orbit, either an extremely large ground-based rectifying antenna would need to be constructed, or a more massive and costly wireless power transmitter aboard the solar satellite would be requisite.

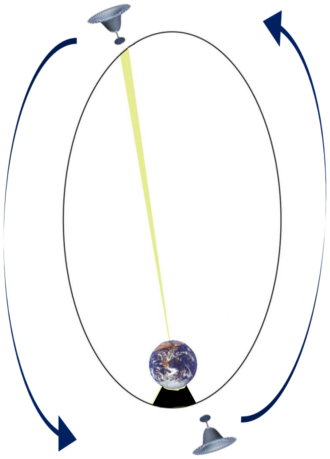


Figure 2: Molniya orbit is an elliptical orbit, employed for extreme latitudes. The power beam is strongest when the satellite is directly over the pole, and weakest as it travels around the opposite pole. To keep a constant power beam positioned on one point, multiple satellites may need to be utilized, to provide power while the other satellite(s) passes through the earth's shadow.

III. Remote Mines Energy Demand and Costs

Understanding the energy demand of remote mines is essential in determining the scale of SSP architecture to center our analysis around. A survey delivered to the energy directors at several mining firms' yields insights about the characteristics of remote operations, and is used to guide the parameters of our DCF analysis. Respondents were asked to consider their firm's remote operation with the highest energy costs and provide information regarding the primary metal mined, host country, cost per kWh, energy source, installed energy capacity on site (a proxy for energy demand), life of mine, and mining method. Several observations can be made from the survey results, as summarized in Table 2. The results are sorted by cost per kWh in ascending order.

Table 2: Remote Mine Characteristics

Country & Metal	Installed Capacity(MW)	Cost per kWh (USD)	Energy Source	Mining Method	Life of Mine (Years)
Mexico - Gold	11 - 20	0.11 – 0.15	Hydro	Open Pit	7
Senegal – Gold	15 – 20	0.16 – 0.20	Diesel	Open Pit	10
Canada - Gold	20	0.21 – 0.25	Natural Gas	Open Pit & Underground	9
Canada - Polymetallic	20	0.21 – 0.25	Diesel	Open Pit & Underground	20
Australia - Polymetallic	20	0.21 – 0.25	Diesel	Open Pit & Underground	9
Mauritania - Gold	20	0.25 – 0.30	Diesel	Underground	15
Congo - Gold	35	0.11 – 0.15	Hydro	Open Pit & Underground	17
Burkina Faso – Gold	50	0.20 – 0.30	Diesel	Open Pit	10
Russia - Copper	301+	0.21 – 0.25	Diesel	Open Pit & Underground	13

Source: Survey results of energy directors of various mining firms

First, two-thirds of the mines have an installed energy capacity of approximately 20 MW. Due to the frequency of this occurrence, we assume energy demand at remote mines of approximately 20 MW for our analysis. Further, the scale of the SSP system selected should deliver approximately 20 MW to Earth's surface to power the mining operation.

Next, the primary metal mined at two-thirds of the 20 MW mines is gold. This occurrence may be due to the small sample size. However, many gold deposits, especially those with high oxide and low sulfide mineralization, are amenable to the low-energy refining process known as cyanide leaching. The least energy-intensive processing method is achieved with run-of-mine dump leaching, where ore is transported directly from the mine to the cyanide leach pad. Less permeable ore requires crude crushing prior to heap leaching. Refining processes that require a greater degree of energy include thermal treatment (roasting) and/or pressure treatment (autoclave) prior to the recovery of gold.[vii]

Also insightful is understanding the cost per kWh that mines pay for electricity. Table 2 shows that mines pay somewhere within a range from $0.11 to $0.30 per kWh. A majority of the mines surveyed pay between $0.21 to $0.30 per kWh. With this finding in mind, for our DCF analysis we assume that the SSP system must deliver power to the mine at a cost of $0.30 per kWh. Utilizing a $0.30 price point allows the SSP IPP to charge up to the maximum that we found a mine to pay per kWh, thus maximizing the revenues that the IPP can collect.

Next, we observe polymetallic mines. Polymetallic mines have no main product, but several economically extractable metals (known as co-products). This is a common occurrence with silver, lead, and zinc deposits, as well as with copper and molybdenum deposits. To process each separate metal on-site requires, in many instances, separate refining circuits for each metal, and is capital intensive. Due to the elevated capital costs required to install multiple processing circuits for each metal, some miners prefer to sell metal concentrates (finely ground ore) to a central refiner, thus reducing the demand for energy at the mine site. Many miners, however, achieve greater revenues by selling a finished metal product, and elect to invest in the technology necessary to produce multiple refined metals, resulting in a greater demand for energy.

Petroleum (Diesel) is the energy source used at 6 out of the 9 mines. This finding supports Al Globus' argument that SSP "need not compete with every ground option and counters the common assumption by critics that SSP must be cost competitive with terrestrial-based solar power.[viii] It only need compete with one commercially successful energy source. For example, in very remote locations diesel generators are routinely used for power. Thus, were SSP cost competitive with diesel in the most remote regions of the world; there would be a niche market for SSP".[ix] Additionally, while not tied to the grid, some mines are benefitted by favorable geographic features such as proximity to rivers or geothermal heat, whereby low-cost energy can be accessed. This scenario is highlighted by the two mines at the top of Table 2.

Over half of the mines possess both an underground and an open pit operation, while the other mines were solely an open pit or underground venture. However, mining method was not found to correlate with elevated levels of energy consumption, but again, this is also likely due to the small sample population of nine respondents.

Life of mine is certainly a characteristic worth considering as mines with longer lives yield greater returns for the IPP, who may then justify the implementation of an SSP system to power the mine. Neil Canby, Executive Director at Sunrise Energy Group, an Australian-based IPP remarks, "the challenge for renewables on off-grid mine sites is financing those projects based on mine life. The benefit of being grid connected is if the mine only has a short mine life, the financier can then sell merchant energy back to the network. In the case of off-grid mines, you need to pack up the solar farm at the end of the mine's life and move it somewhere else or risk it becoming a stranded asset."[x]

It should be noted also that the life of mine fluctuates as economic conditions change. These economic conditions consist of changes in the metal price, discovery of additional reserves near the mine, acquisition of nearby properties, changes in mining and processing capacity (investment in larger equipment) among others. Given that these changes are often unpredictable, the life of mine stated in the project's feasibility study is likely to change, introducing risks and opportunities in installing an SSP system from the outset of a mining operation. For example, Newcrest's Wafi-Golpu mine in Papua New Guinea. In its 2007 Pre-Feasibility Study (PFS), the project had an estimated life of mine of nine years, where the price of gold used in the evaluation was $520/oz.[xi] In 2012, another PFS was published for the project and the life of mine was updated to 26 years[xii], where the price of gold used in the evaluation was $1,250/oz.[xiii] Metal price influences the mine's cut-off grade, or "the criterion that discriminates between ore and waste within a given mineral deposit."[xiv] As price increases, a greater volume of material becomes profitable to extract, and contrastingly, as a metal price decreases, less material becomes profitable to extract. Just as a mine's life can increase, it can decrease due to changes in economic conditions.

IV. Discounted Cash Flow (DCF) Evaluation

What is Discounted Cash Flow Evaluation?

Discounted cash flow (DCF) evaluation is a common investment decision-making method employed by financial analysts and business managers. DCF evaluation takes into consideration the time value of money and project risk. Time value of money accounts for weighted average cost of capital (WACC), inflation, and opportunity costs. Put simply, WACC is the return a firm requires to decide if an investment meets capital return requirements. It is an amalgam of equity capital and debt capital. Inflation is the rate at which the purchasing power of a currency is decreasing, due to rising prices for goods and services in an economy. Opportunity costs are the losses of potential gains from other investment alternatives, when one investment is already made. As a simple illustration, an investor would rather receive $1,000 today compared to $1,000 six months from today. The delay in receiving $1,000 results in a loss because the investor could have employed that $1,000 in another investment for those six-months, generating returns.

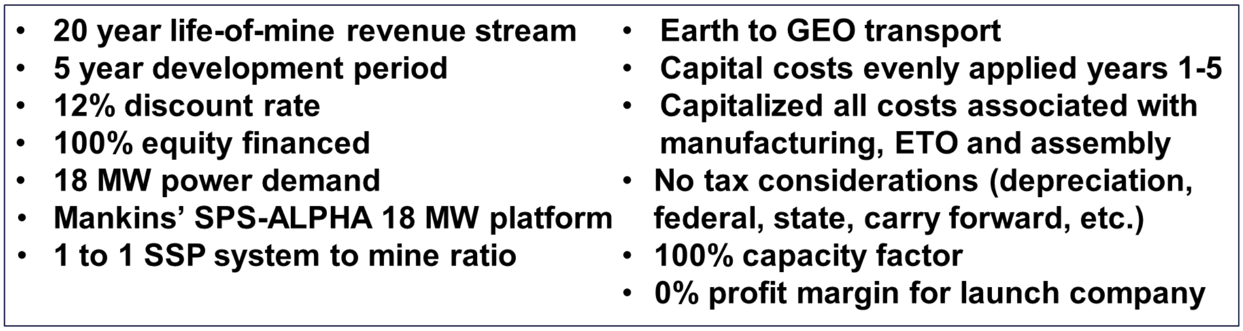
Project risk, or investment risk, takes into consideration the premium that investors demand for owning a particular asset. Some investments are inherently riskier than others. For example, investing in a snack machine at an office complex requires a lower return than an investment in an interplanetary transportation system. The snack machine investment has been replicated thousands of times, and has demonstrated ability to produce returns; whereas the successful deployment of an interplanetary transport system has yet to be accomplished. As such, the transport system investment is riskier and must yield a greater return to investors.

Discounted cash flow evaluation uses a discount factor, which accounts for time value of money and project risk factors previously discussed. Each period of a project generates positive, negative, or zero cash flows. Each subsequent period’s cash flows are discounted by the same factor to show what the investment will return at the end of each period in today’s dollars. The aggregate of these individual cash flows is the investment’s net present value (NPV). If the NPV of an investment is greater than 0, it is considered economically feasible. If NPV is 0 or negative, it is considered not economically feasible, and the project should be rejected. Usually accompanying the NPV metric is the internal rate of return (IRR) metric, which shows the percentage return that the investment yields. An IRR greater than the discount factor is generally acceptable, whereas any other IRR metric would be considered not economically feasible. Generally, NPV is the preferred project acceptability metric, as it reflects the actual cash that a project generates, whereas IRR merely reflects a rate at which cash returns to a firm.

Assumptions for Our Evaluation

The assumptions made in our analysis are aimed to provide a realistic case scenario for economic feasibility. Below is a brief explanation of the assumptions used. Figure 3 shows a summary of the assumptions that guide our evaluation. We generally try to make optimistic assumptions to illustrate the best possible case for SSP.

Figure 3: Main Assumptions of the DCF Analysis



- **20 year life-of-mine revenue stream**
- **5 year development period**
- **12% discount rate**
- **100% equity financed**
- **18 MW power demand**
- **Mankins’ SPS-ALPHA 18 MW platform**
- **1 to 1 SSP system to mine ratio**
- **Earth to GEO transport**
- **Capital costs evenly applied years 1-5**
- **Capitalized all costs associated with manufacturing, ETO and assembly**
- **No tax considerations (depreciation, federal, state, carry forward, etc.)**
- **100% capacity factor**
- **0% profit margin for launch company**

20-year mining operation: The time that a relatively long-lived gold mine operates, allowing the IPP a reasonable amount of time to earn a profit on its capital investment.

5-year construction/launch/assembly: Prior to providing power, the system must first be manufactured, transported to GEO and assembled. 5 years is a reasonable timeframe to expect development.

Discount rate of 12%: Discount rates between 10% - 15% are fairly common for capital projects of this scale. It is reasonable to expect that 12% accounts for the cost of equity capital and project risk for SSP.

100% equity financing: Assuming the project is 100% equity financed reveals whether the project is feasible without the infusion of borrowed dollars, and is the approach used by most companies. Stermole, Stermole, and Pederson[xv] further explain the advantages of evaluating cash flows under this assumption. “Since more and more leverage gives higher and higher

[ROR] results, the use of leveraged economic analysis results for decision making purposes can sometimes mislead the decision-maker into thinking a marginal project is a better project than it actually is. For this reason there is considerable merit in making zero leverage, the cash investment case as the common basis for comparing all investment opportunities." An additional advantage of assuming no-debt financing is that it does not require one to know the project's financing conditions at the time of the analysis. Financing arrangements typically are not determined until just before a project commences. 100% equity financing analysis eliminates these presumptions.

$0.30 per kWh: Mines that rely on diesel typically pay between $0.20 and $0.30 per kWh. A cost of $0.30 per kWh to the mining customer maximizes the IPP's revenues.

18 MW demand at mine site: Many of the mines surveyed had an installed capacity onsite of 20 MW, which was used to determine energy demand. 18 MW demand coincides with the power output of a well-documented and thoroughly explained system designed by John Mankins.

Mankins' SPS-ALPHA DRM 3/Case 2 18 MW platform: Mankins' SPS-ALPHA DRM3/Case 2 platform is designed to transmit 18 MW to the earth's surface, which is reasonably close to the 20 MW energy demand for the majority of the mines surveyed. In late 2017, Mankins published a paper, summarizing technologic updates to the SPS-ALPHA concept, which he refers to as SPS-ALPHA Mark-II.[xvi] The results appear to be more favorable to feasibility than the concepts analyzed in our study, however specific details regarding updated costs were not available from the author. Mankins' forthcoming book on the SPS-ALPHA Mark-II concept would be worth studying for cost, mass, scale, and performance details.

1 to 1 SSP system to mine ratio: We studied the feasibility of one SSP system designated to one remote mine with twenty-four hour per day coverage. One satellite to multiple mines is studied in the section titled "Other Business Cases".

Geosynchronous orbit: Geosynchronous orbit (GEO) would require the manufacture, launch, and assembly of only one solar power satellite. Single mine dedicated SPS. LEO would require more than one SPS to be assembled, transported and assembled, resulting in additional launch costs. It also implies that the location of the mine is nearer the equator than an extreme latitude. Mines in extreme latitudes may require multiple SPS in a Molniya orbit, due to orbital mechanics, ultimately increasing costs.

Capital costs evenly distributed across years 1-5: This assumption simplifies the cost schedule, as it assumes uniformity in annual cash outflows. It also implies that manufacturing and transport to GEO are simultaneously occurring.

Capitalized all costs associated with manufacturing and transportation: Costs incurred during the construction of an asset that are directly attributable to placing it into service should be capitalized.

No tax considerations: If the project is not found to be economically feasible prior to tax considerations, it is not likely to be considered feasible after taxes are applied. Additionally, tax regimes vary from nation to nation, and the United States is not the only jurisdiction from which an IPP could deploy an SSP system.

100% capacity factor: To maximize revenues, the system should be producing at full capacity (18 MW) every second of every day.

0% profit margin for launch company: While this assumption is not entirely realistic, it aids in understanding the minimum cost to an IPP for transporting the SPS payload to GEO. While the transport company is not making a profit in this scenario, they are not losing money.

Revenues

The revenue calculation is straightforward, and is invariable in each model we analyzed. Revenues do not fluctuate year to year, given that a PPA provides the IPP with a contracted energy sales price throughout the duration of the agreement. Revenue is the product of annual megawatt hours produced (MWh) and electricity price. Annual MWh is the product of the capacity of the system (18 MW), number of hours in a year (8,760), and an assumed capacity factor of 100%, resulting in annual production of 157,680 MWh. Electricity price is the cost per megawatt hour, or cost per kilowatt hour ($0.30) multiplied by a factor of 1000 ($300 per MWh). Therefore, gross revenue is the product of 157,680 MWh and $300 per MWh, resulting in revenues of $47.3 million per year for the life of the project (20 years). Without discounting, total revenues would be $993.4 million. However, with a WACC of 12%, the net present value (NPV) of the revenues are $227.3 million.

Costs

Various methods were employed to estimate costs associated with manufacturing an 18 MW SSP assembly and transporting it to GEO. Manufacturing costs are invariable in each case analyzed. Earth to GEO transportation costs vary depending on the transportation technology employed. SpaceX's Falcon Heavy (FH) and Big Falcon Rocket (BFR) transportation assemblies are investigated, given the company's optimistic claims of significantly reducing the cost per kilogram of reaching orbit. Each case analyzed utilizes Mankins' SPS-ALPHA DRM 3/Case 2 manufacturing cost assumptions, or some slight modification of these assumptions, summarized in Table 3.[xvii] The ETO cost examples investigated include a base case, a Falcon Heavy reusable case, a Falcon Heavy expendable case, and a BFR reusable case. Prior to discussing the DCF analysis, the underlying manufacturing, transport and other cost assumptions are explained.

Manufacturing Costs

Proponents of SSP argue that the manufacturing of thousands of identical components will yield conditions conducive to achieving economies of scale, where the average cost of each unit produced declines as the scale of production increases to a point. This scenario generally implies that the production process is highly automated, and the input of labor is minimal. Mankins assumes a "manufacturing curve" of 66% in his cost estimates for SPS-ALPHA.[xviii] Argote and Epple explain, "as organizations produce more of a product, the unit cost of production typically decreases at a decreasing rate. This phenomenon is referred to as a learning curve, a progress curve, an experience curve, or learning by doing".[xix] They further explain that, "each doubling of cumulative output leads to a reduction in unit cost to a percentage, of its former value".[xx] Thus a 66% manufacturing curve means that each doubling of output leads to a 34% reduction in unit cost. The aim of this report is not to determine whether this assumption is realistic, but to determine economic feasibility of SSP given the assumptions made.

Table 3 shows the totals for manufacturing cost and total mass of the 18 MW system, along with the number of components required for the platform. The Final CER column shows the cost per kilogram, subject to the "manufacturing curve", and also represents the high-end of Mankins' cost estimate range for each kilogram.

Table 3: Manufacturing Cost Assumptions

SPS-ALPHA DRM 3/Case 2	Final CER ($/kg)	Unit Mass (kg)	Number of Modules	Total mass (kg)	Manufacturing Cost Totals
HexBus Modules	700	24	10,301	247,224	$ 173,056,800
Interconnects	200	1	61,782	61,782	12,356,400
HexFrame Structure	800	55	552	30,360	24,288,000
Reflector / Pod	4,000	80	113	9,040	36,160,000
Solar Power Gen Mod.	700	21	10,019	210,399	147,279,300
Wireless Power Trans.	700	47	9,919	466,193	326,335,100
Prop and Attitude Control	9,000	36	100	3,600	32,400,000
MPPR Arms	6,000	10	237	2,370	14,220,000
.5 year prop load	400	130	100	13,000	5,200,000
Total				**1,043,968**	**$ 771,295,600**

Other Costs

Other Costs are comprised of ground receiver (rectenna) installation and miscellaneous ground operations. This figure is the difference of Mankins' estimated total costs of $4.5 billion and the manufacturing and transport costs, resulting in $596,800,400. These costs are held constant in each case considered.

Earth to Geosynchronous Orbit Costs

For the SpaceX vehicles, transport costs from Earth to geostationary transfer orbit (GTO) assumes no discounts, and that the customer pays only for the kilograms transported, rather than paying the full launch cost of a vehicle loaded to capacity, as that vehicle could also be loaded with another firm's freight. Additionally, SPS ALPHA is designed to operate in GEO, rather than GTO, which is an additional Δv of 1.47. However, as with Mankins, we assume that the payload will make its way from GTO to GEO by means of solar electric propulsion, and allows us to ignore additional transportation costs.

Base Case

Mankins assumes $1,500 kg to LEO and an additional $1,500 / kg to GEO. Giving a total of $3,000 per kg to GEO. Mankins' base case also assumes that the transport system is reusable and highly fuel-efficient, possibly powered by solar electric propulsion. These assumptions lead to Earth to Geo costs of $3.1 billion. The breakdown of assumptions are listed in Table 4.

Table 4: Base Case Assumptions

DRM 3/Case 2 Mankins' Assumptions	
Total Platform Mass (kg)	1,043,968
Manufacturing Cost / kg ($)	$ 739
Cost / kg to GEO ($)	$ 3,000
Cost Summary	
Launch costs Earth to GEO	**$ 3,131,904,000**
Manufacturing Costs 18 MW SPS-ALPHA	**$ 771,295,600**
Other Costs	**$ 596,800,400**
Total Manufacturing and Transport Costs	**$ 4,500,000,000**

Falcon Heavy Reusable

The Falcon Heavy reusable data is sourced from the SpaceX website.[xxi] The system assumes a payload capacity of 8,000 kg to GTO, resulting in 131 launches to put the total system mass (1,043,968 kg) into orbit. The breakdown in cost assumptions are given in Table 5.

With a cost of $90 million per mission, Earth to GTO transport totals are $11.7 billion, or $11,250 per kg. Based off the Falcon Heavy webpage, it can be inferred that the $90 million launch cost includes a customer markup, and is not the cost to SpaceX. However, the company is not forthcoming with their desired profit margin, thus it is assumed for our analysis that a launch costs are $90 million. In accordance with our best-case scenario for our analysis we assume a 0% profit margin for the rocket company.

This cost also assumes no discounts, and that the IPP only pays for the kilograms transported, rather than paying the full launch cost of a vehicle that is loaded to capacity, as that ship could also be loaded with another firm's freight. With a 20% discount applied for a multiple mission contract, the Earth to GTO costs are roughly $9.4 billion, or $9,000 per kg.

Table 5: Falcon Heavy Reusable Assumptions

DRM 3/Case 2 with Falcon Heavy Reusable	
Total Platform Mass (kg)	1,043,968
Falcon Heavy payload capacity (kg) to GEO	8,000
Earth to GEO trips	131
Cost per launch - 0% profit margin ($)	$ 90,000,000
Cost / kg to GEO ($)	$ 11,250
Launch costs Earth to GEO (launches * cost per launch) ($)	$ 11,790,000,000
Cost Summary	
Launch costs Earth to GEO (total kg costs)	**$ 11,744,640,000**
Manufacturing Costs 18 MW SPS-ALPHA	**$ 771,295,600**
Other Costs	**$ 596,800,400**
Total Manufacturing and Transport Costs	**$ 13,112,736,000**

Falcon Heavy Expendable

The Falcon Heavy expendable vehicle can carry an estimated 26,700 kg t GTO, requiring 40 launches. At a cost of $150 million per launch, total Earth to GTO costs are about $5.9 million, or $5,618 per kilogram.[xxii] With a 20% multiple mission discount GTO costs are 4.7 million or 4,500 per kg. Although the cost of a fully expendable Falcon Heavy vehicle is two-thirds more per launch than the reusable Falcon Heavy vehicle, the carrying capacity increase of over 200% requires 70% fewer launches, resulting in half the GTO costs of the Falcon Heavy reusable system. GTO to GEO? 10% increase. The breakdown in cost assumptions are given in Table 6.

Table 6: Falcon Heavy Expendable Assumptions

DRM 3/Case 2 with Falcon Heavy Expendable	
Total Platform Mass (kg)	1,043,968
Falcon Heavy payload capacity (kg) to GEO	26,700
Earth to GEO trips	40
Cost per launch - 0% profit margin ($)	$ 150,000,000
Cost / kg to GEO ($)	$ 5,618
Launch costs Earth to GEO (launches * cost per launch) ($)	$ 6,000,000,000
Cost Summary	
Launch costs Earth to GEO (total kg costs)	**$ 5,864,988,764**
Manufacturing Costs 18 MW SPS-ALPHA	**$ 771,295,600**
Other Costs	**$ 596,800,400**
Total Manufacturing and Transport Costs	**$ 7,233,084,764**

BFR Reusable

SpaceX's much-hyped Big Falcon Rocket (BFR) is yet in development, and is expected to begin testing in 2019. Due to the lack of official data on the BFR system, speculation and a broad difference of opinions abound concerning the actual costs and payload capacity associated with the system's various logistical configurations (orbital refueling, no refueling, etc.). As such, cost and payload figures are sourced from a combination of public SpaceX presentations and non-SpaceX affiliated space enthusiasts; therefore, scrutiny and disagreement over the figures used are expected. Additionally, many experts argue that SpaceX's published cost per kg claims are based on forecasts of a matured launch operation, and are thus low by at least an order of magnitude. However, we proceed with our cost estimate for the BFR reusable case. For our analysis, we assume an estimated 18,000 kg payload to GTO,[xxiii] and an estimated $11.1 million per launch.[xxiv] With these metrics, the cost of transporting the SPS components to GTO is $643.8 million, or $617 per kg; substantially less than any launch system configuration analyzed thus far. The breakdown in cost assumptions are given in Table 7.

Table 7: BFR Reusable Cost Assumptions

DRM 3/Case 2 with BFR Reusable	
Total Platform Mass (kg)	1,043,968
Falcon Heavy payload capacity to GEO (kg)	18,000
Earth to GEO trips	58
Cost per launch - 0% profit margin ($)	$ 11,100,000
Cost / kg to GEO ($)	$ 617
Launch costs Earth to GEO (launches * cost per launch) ($)	$ 643,800,000
Cost Summary	
Launch costs Earth to GEO (total kg costs)	**$ 643,780,267**
Manufacturing Costs 18 MW SPS-ALPHA	**$ 771,295,600**
Other Costs	**$ 596,800,400**
Total Manufacturing and Transport Costs	**$ 2,011,876,267**

DCF Analysis

Now that the framework for revenue and costs have been established, discounted cash flow evaluation can be performed on the 18 MW SPS-ALPHA system applied to a remote mining operation. Revenues are a constant $47.3 million each year over the life of the 20 year PPA. Each Earth to GEO transport case is evaluated in isolation and compared to determine the most viable system. Additionally, a breakeven analysis is discussed. As a frame of reference, a Net Present Value (NPV) greater than $0.00, and a Rate of Return (ROR) greater than 10% are generally considered feasible criteria.

Base Case

By incorporating revenues and Mankins' cost assumptions into the DCF evaluation, a net present value (NPV) of -$3.4 billion and a rate of return of -10% is ascertained. Table 7 shows an abbreviated summary of the cash flows from the project. Years 0 – 4 represent the $4.5 billion investment spread evenly across five years. Years 5 – 25 reflect the consistent year-over-year revenues associated with the 20-year power purchase agreement (PPA), and the steady energy demand from the mining customer. Note the row labeled "Discounted Cash Flow". The cash flows are discounted by 12% year-over-year. After discounting, the revenues in year 5 have a present value of $26.84 million. By year 25 the present value of revenue is a mere $2.78 million.

Table 7: Summary of Discounted Cash Flow-Base Case

	Units	0	1	2	3	4	5	24	25
Discount Rate	12%								
Gross Revenue	M$	-	-	-	-	-	47.30	47.30	47.30
Capital Costs	M$	(900.00)	(900.00)	(900.00)	(900.00)	(900.00)	-	-	-
Cash Flow	M$	(900.00)	(900.00)	(900.00)	(900.00)	(900.00)	47.30	47.30	47.30
Discounted Cash Flow	M$	(900.00)	(803.57)	(717.47)	(640.60)	(571.97)	26.84	3.12	2.78

Decision Metrics	
ROR	- 10%
NPV	- $3.40 billion

Falcon Heavy Reusable

The DCF evaluation of the Falcon Heavy reusable system yields an NPV of -$10.4 billion, and an ROR of -15%. A summary of the results are found in Table 8. This is a deterioration of the financial results from the base case, thus this system looks to be a worse option.

Table 8: Summary of Discounted Cash Flow-Falcon Heavy Reusable

	Units	0	1	2	3	4	5	24	25
Discount Rate	12%								
Gross Revenue	M$	-	-	-	-	-	47.30	47.30	47.30
Capital Costs	M$	(2,622.55)	(2,622.55)	(2,622.55)	(2,622.55)	(2,622.55)	-	-	-
Cash Flow	M$	(2,622.55)	(2,622.55)	(2,622.55)	(2,622.55)	(2,622.55)	47.30	47.30	47.30
Discounted Cash Flow	M$	(2622.55)	(2,341.56)	(2,090.68)	(1,866.68)	(1,666.68)	26.84	3.12	2.78

Decision Metrics	
ROR	- 15%
NPV	- $10.40 billion

Falcon Heavy Expendable

The Falcon Heavy Expendable system is significantly more favorable than the Falcon Heavy Reusable system. A summary of the results can be found in Table 9. The trade-off of transporting more mass per launch versus replacing launch vehicles at $150 million per mission actually benefits the business case. However, a NPV of -$5.6 billion and an ROR of -12% are not economically viable.

Table 9: Summary of Discounted Cash Flow-Falcon Heavy Expendable

	Units	0	1	2	3	4	5	24	25
Discount Rate	12%								
Gross Revenue	M$	-	-	-	-	-	47.30	47.30	47.30
Capital Costs	M$	(1,446.62)	(1,446.62)	(1,446.62)	(1,446.62)	(1,446.62)	-	-	-
Cash Flow	M$	(1,446.62)	(1,446.62)	(1,446.62)	(1,446.62)	(1,446.62)	47.30	47.30	47.30
Discounted Cash Flow	M$	(1,446.62)	(1,291.62)	(1,153.23)	(1,029.67)	(919.35)	26.84	3.12	2.78

Decision Metrics	
ROR	- 12%
NPV	- $5.60 billion

BFR Reusable

The Big Falcon Rocket (BFR) reusable case presents the best business case for SPS-ALPHA DRM3/Case 2, provided all claims and assumptions regarding its costs and performance are accurate. By utilizing reusable BFR vehicles to deliver the 1,043,960 kg payload to GTO, the NPV is -1.4 billion, and the ROR to -5%. While these metrics fail to meet general investment criteria, they are significantly higher than the other cases evaluated, and are not outside the realm of feasibility if transport technology continues to advance, and the accompanying costs continue to fall.

Table 9: Summary of Discounted Cash Flow-Big Falcon Rocket Reusable

	Units	0	1	2	3	4	5	24	25
Discount Rate	12%								
Gross Revenue	M$	-	-	-	-	-	47.30	47.30	47.30
Capital Costs	M$	(402.38)	(402.38)	(402.38)	(402.38)	(402.38)	-	-	-
Cash Flow	M$	(402.38)	(402.38)	(402.38)	(402.38)	(402.38)	47.30	47.30	47.30
Discounted Cash Flow	M$	(402.38)	(359.26)	(320.77)	(286.40)	(255.72)	26.84	3.12	2.78

Decision Metrics	
ROR	- 5%
NPV	- $1.40 billion

A comparison of all of the DCF cases is given below in Table 10. As discussed already, the best option from these cases in the BFR.

Table 10: Comparison of Discounted Cash Flow Results across cases

Decision Metrics	Unit	Base Case	Falcon Heavy Reusable	Falcon Heavy Expendable	BFR Reusable	Acceptable Metrics
Discounted Cash Flow ROR	%	-10%	-15%	-12%	-5%	> 12%
Net Present Value	(M$)	$ (3,406)	$ (10,361)	$ (5,613)	$ (1,397)	> $ 0.00
Maximum Cash Exposure	(M$)	$ (3,634)	$ (10,588)	$ (5,840)	$ (1,625)	-
Breakeven Investment	(M$)	$ 281.5	$ 281.5	$ 281.5	$ 281.5	-

Breakeven Analysis

It is one thing to say that a project is not economically feasible, however it is much more informative to understand what costs need to be for the project to be considered economically feasible. In our breakeven analysis, revenues are held constant at $47.3 million due to the twenty-year power purchase agreement, but costs and system mass were reevaluated to determine the system's breakeven figures, relative to Mankins' base case. If revenues were altered, the price per kWh would need to increase by 1,500% to breakeven. This scenario seems unlikely to the authors, so we focus on varying costs. By performing iterative calculations, we found that the system's NPV equals 0 when total costs equal $281.5 million, or a reduction of 94%. Note in Table 11 the required rate of return to yield an NPV of $0.00 is 12%, or the discount rate. The NPV of $0.00 is assumed in order to come up with a breakeven cost figure.

If the costs proportions were kept the same as in the Base Case (manufacturing, GEO transport, and other costs comprise 17%, 70%, and 13% of total costs), then the breakeven costs for manufacturing, GEO transport, and other are $48.3 million, $195.9 million, and $37.3 million, respectively. With these figures, we analyzed a cost reduction approach and a mass reduction approach to determine breakeven parameters. The results are discussed below and summarized in Table 12.

The cost reduction analysis implies that technologic breakthroughs in transport systems are required to meet the breakeven target. While manufacturing and other costs are held constant, GEO transport costs per kilogram must decrease from $3,000 to $188, assuming the system's mass remains unaltered at 1,043,968 kilograms.

The mass reduction analysis implies technologic advancement in the materials used in fabricating the system while still costing $48.3 million to manufacture. Iterative calculations determined that mass must also fall by 94%, and total 65,315 kilograms to achieve an NPV equal to $0.00. The cost per kilogram of transporting this system to GEO remains $3,000, but would require fewer launches.

Table 11: Breakeven Costs Case Summary

	Units	0	1	2	3	4	5	24	25
Discount Rate	12%								
Gross Revenue	M$	-	-	-	-	-	47.30	47.30	47.30
Capital Costs	M$	(56.31)	(56.31)	(56.31)	(56.31)	(56.31)	-	-	-
Cash Flow	M$	(56.31)	(56.31)	(56.31)	(56.31)	(56.31)	47.30	47.30	47.30
Discounted Cash Flow	M$	(56.31)	(50.27)	(44.89)	(40.08)	(35.78)	26.84	3.12	2.78

Decision Metrics	
ROR	12%
NPV	$ 0.00

Table 12: Breakeven Cost Case Breakdown

Breakeven Cost Analysis		
	Cost Reduction Case	**Mass Reduction Case**
Manufacturing Cost (Million $)	$ 48.3	$ 48.3
Other Cost (Million $)	$ 37.3	$ 37.3
GEO Transport Cost ($/kg)	$ 188	$ 3,000
Mass (kg)	1,043,968	65,315
Total Cost (Million $)	$ 281.5	$ 281.5

V. Other Business Cases

Other business cases ought to be considered in evaluating the feasibility of SSP. We also investigated a carbon tax case, and a mining district case. Carbon taxes increase the cost per kWh that mines would be accustomed to, justifying an increased cost per kWh that IPPs could charge a mine, increasing revenues. The mining district case could potentially increase the IPP's revenues by the signing of multiple PPAs from multiple customers in close geographic proximity.

Carbon Tax Case

The implementation of carbon taxes, or carbon emission penalties in various jurisdictions across the globe, increases the costs associated with burning fossil fuels for power. Mines operating in these jurisdictions, such as Fortune Minerals' NICO project in the Northwest Territories, will be paying roughly 15% more per kWh, increasing the price IPPs could charge these customers, improving revenues. Here, we evaluate the impact of carbon taxes on the feasibility of SSP. We assume a 15% increase in the cost per kWh, and the BFR reusable cost structure. Revenues improve from an undiscounted $47.3 million to $54.4 million. Table 13 shows the results of this analysis. While increasing revenues by 15% slightly improves ROR and NPV from the BFR reusable case, the decision criteria remain unattractive.

Table 13: Carbon Costs Discounted Cash Flow Summary

	Units	0	1	2	3	4	5	24	25
Discount Rate	12%								
Gross Revenue	M$	-	-	-	-	-	54.40	54.40	54.40
Capital Costs	M$	(56.31)	(56.31)	(56.31)	(56.31)	(56.31)	-	-	-
Cash Flow	M$	(56.31)	(56.31)	(56.31)	(56.31)	(56.31)	54.40	54.40	54.40
Discounted Cash Flow	M$	(56.31)	(50.27)	(44.89)	(40.08)	(35.78)	30.87	3.58	3.20

Decision Metrics	
ROR	- 4%
NPV	- $1.36 billion

Mining District Case

Every so often a new mining district is discovered and established. When the first mineral deposit is discovered, other exploration outfits become excited about the prospects of finding a deposit in the same geologic neighborhood, and acquire land nearby. As several of these mineral deposits are determined to be economically feasible to extract and refine, the minerals become classified as reserves, and the deposits typically become mines. When several mines come on-line in the same area, within a few years of each other, an opportunity for a shared energy infrastructure becomes present. This scenario is represented by the revival the Golden Triangle in British Columbia’s northwest corner, in recent years.

Table 14: Summary of Discounted Cash Flow Results-Multiple Mines

System Comparison – Each Utilizing BFR Reusable Transport				
Metric	**Unit**	**1 Customer 18 MW System**	**4 Customers 72 MW System**	**10 Customers 500 MW System**
IRR	%	-5.00%	-3.4%	8.3%
NPV	(M$)	$ (1,397)	$ (4,214)	$ (2,466)

We thought it pertinent to evaluate whether SSP would be a feasible energy source for a mining district. The scenario enables the IPP to secure PPAs from multiple customers, multiplying revenues. This requires a larger SSP platform, capable of delivering more power to the Earth’s surface, and requires greater investment. However, with the application of a manufacturing curve, which causes costs to increase at a smaller rate than revenues, which as it may logically seem, would result in a scenario where revenues would eventually eclipse costs. However, after modelling our assumptions, we found that NPV worsens, becoming further negative, while IRR improves, due to the discounting of cash flows. The increased costs of commissioning a larger system in years 1-5 are discounted to a lesser degree than the associated revenues, which do not begin until year 6 and continue through year 25.

We examined a four-customer scenario, requiring 18 MW each, while utilizing the same SPS-ALPHA system, but scaled up to 72 MW with a 66% manufacturing curve. This system was also paired with the favorable BFR launch assumptions. By increasing revenues by a factor of 4, and increasing costs by a factor of 2.15, it would seem likely that the system would trend toward feasible. However, the IRR is -3.38% and the NPV is $ -4.2 billion. This worsening NPV is due to discounting the cash flows. The increased upfront costs of commissioning a larger system in years 1-5 are discounted to a lesser degree than the associated revenues, which do not begin until year 6 and continue through year 25. Further details of the assumptions of this analysis are discussed in the Appendix.

We also investigated a 10-customer scenario, requiring 50 MW each. For this arrangement, we utilized Mankins' cost-friendly estimates for SPS-ALPHA DRM 4/Case 1, an upgraded 500 MW system.[xxv] This system was selected for evaluation given that its estimated manufacturing costs are significantly lower than the 18 MW system scaled-up to 500 MW. This system was also paired with the BFR reusable transport system to yield the lowest total cost. The decision metrics yield an IRR of 8.3%, but an NPV of $ -2.5 billion. While seeing a positive IRR seems desirable, a negative NPV ultimately shows that the project is not recovering it's cost of capital. However, an 8.3% return is reasonable for social (I.e., government) investments.

A larger system was not evaluated because Mankins' next largest proposed system is a 2 GW scale, and would require 5 mining customers each demanding 400 MW in a relatively small geographic area, which is an unlikely occurrence. It is possible that further economies of scale for even larger systems would yield positive NPV's. However, it is not obvious what sources would demand gigawatt-scale electricity at high electricity prices. One possibility might be islands which rely on diesel generation.

VI. Conclusions and Recommendations for Further Work

Remote mines could greatly benefit from SSP's conceptual benefits, and would make an ideal pilot market for SSP technology. A renewable power source with round-the-clock capabilities would save the capital costs of installing a petroleum fuel power generation system, while purchasing power from an IPP. SSP would allow mining firms to hedge against oil price volatility, by securing a long-term cost of power through a PPA, reducing operating expenses.

Further, the mine's carbon footprint would be virtually zero, sparing the mine from punitive taxes in several jurisdictions. Where remote operations have hybridized their diesel power generation with renewables, some mines face intermittency challenges and rely more heavily on diesel power than the installed wind or solar power systems. SSP does not face the same intermittency problems, with an estimated capacity factor nearing 100%. While SSP's benefits are desired by remote mines, its economic feasibility is problematic.

Based on the authors' assumptions regarding costs, revenues and system performance, Mankins' SPS-ALPHA DRM 3/Case 2 space solar power platform is not currently an economically viable power source for remote mining customers. After evaluating several transportation vehicles we determined that SpaceX's BFR reusable transport system reduces costs by over 50% from Mankins' 2012 estimates. To be considered economically feasible under our framework, total costs must be reduced by 94%, to $281.5 million, and revenues must equal $47.3 million per year. A favorable cost environment implies that either costs or system mass must decrease. Earth to GEO transport costs must fall to $188 per kg from Mankins' estimate of $3,000 per kg, or the system's mass must be reduced to 65,315 kg, from 1,043,968 kg.

Our study focused specifically on Mankins' SPS-ALPHA DRM 3/Case 2 platform, as its design and cost estimates were well explained, and its delivered power is consistent with that demanded by many remote mines. The study was not exhaustive as it relates to various SSP platforms. A multitude of other SSP platforms have been proposed by various organizations and governments in recent years that are worth evaluating for economic feasibility as potential power sources for mining operations. A handful of these proposed platforms are listed below.

- David Hyland's *Hyland Power Star* [xxvi]
- China Academy of Space Technology's *Multi-Rotary Joints SSP* [xxvii]
- Keith Henson's *Team Sunflower Skylon Thermal Power Satellite* [xxviii]
- Xidian University's *SSPS-OMEGA* [xxix]
- IUPUI's *Tin Can SPS* [xxx]
- California Institute of Technology and Northrop Grumman's *SSPI* [xxxi]
- Ian Cash and SICA Design Limited's *CASSIOPeiA Solar Power Satellite* [xxxii]

As mentioned previously, John C. Mankins has updated and improved the design of SPS-ALPHA, and calls the new architecture SPS-ALPHA Mark-II. Detailed cost and performance updates are expected to be published in Mankins' forthcoming second edition of "*The Case for Space Solar Power*". A reevaluation of the updated architecture for use in remote mining applications is recommended.

Research and development of ultra-lightweight photovoltaic materials within the last decade has yielded technologies suitable for use in SSP.[xxxiii] As these technologies mature, a study of the associated costs of producing these materials for an SSP system is recommended, as are the consequent effects on the transport costs to geostationary orbit.

Currently, Earth to GEO transport vehicles consist of rockets utilizing chemical propulsion technology. As new breakthroughs and developments in Earth to orbit solutions emerge, feasibility of SSP as a power source for remote mines ought to be evaluated. A final point is that advocates of using space resources (metals and silicon from the Moon and recycled space debris) and in-space manufacturing technologies to build large solar power structures in space suggest that construction costs can be substantially reduced by not having to launch all material from Earth.

---

[i] Al Globus. “Towards an Early Profitable PowerSat, Part II”. International Space Development Conference, 2011, p.2, available from http://space.alglobus.net/papers/TowardsAnEarlyProfitablePowerSatPartII.pdf

[ii] John C. Mankins. “SPS-ALPHA: The First Practical Solar Power Satellite via Arbitrary Large Phased Array (A 2011-2012 NASA NIAC Phase 1 Project).” Santa Maria, CA: Artemis Innovation Management Solutions LLC. September 15, 2012. p. 47.

[iii] Energy Information Administration. Today in Energy: Low Wholesale Power Prices Reduce Quark Spread for Nuclear Operators. URL https://www.eia.gov/todayinenergy/detail.php?id=10971. Accessed 14 August, 2018.

[iv] Energy Information Administration. Henry hub natural gas spot price, 2017c. URL http: //tonto.eia.gov/dnav/ng/hist/rngwhhda.htm. Accessed 2 July, 2017.

[v] Lobo, Jose Antonio. Interview by Andrew Slavin, Energy and Mines. Controlling Mining’s Exposure to Volatile Fuel Prices with Renewables, 29 March, 2016. http://energyandmines.com/2016/03/controlling-minings-exposure-to-volatile-fuel-prices-with-renewables/. Accessed 10 July, 2018.

[vi] Priest, Warner. Interview by John McCloy, Energy and Mines. Autonomous Microgrids Offer Reliable, Cost-Effective Power to Remote Mining Operations. 19 June, 2018. http://australia.energyandmines.com/files/Brochure-Energy-and-Mines-02.pdf. Accessed 10 July, 2018.

[vii] La Brooy, S.R.; Linge, H.G.; Walker, G.S., “Review of Gold Extraction from Ores”. Minerals Engineering, Volume 7, Issue 10, 1994, Pages 1213-1241, ISSN 0892-6875, available from https://doi.org/10.1016/0892-6875(94)90114-7.

[viii] S. Fetter, Space Solar Power: An Idea Whose Time Will Never Come?
Phys. Soc. 33 (1) (2004) 10–11.

[ix] Al Globus, “Towards an Early Profitable PowerSat, Part II”, International Space Development Conference, 2011, p.2, available from http://space.alglobus.net/papers/TowardsAnEarlyProfitablePowerSatPartII.pdf

---

[x] Canby, Neil. Interview by John McCloy, Energy and Mines. Towards Profitable, Zero-Emissions Mining: Q&A with Sunrise Energy Group. 5 June, 2018. http://australia.energyandmines.com/files/FEATURE-Australia-2018-Sunrise-v2-web.pdf. Accessed 10 July, 2018.

[xi] AMC Mining Consultants Limited (2011) Technical report. Technical Report on Wafi-Golpu Property in Morobe Province Papua New Guinea. AMC 711037. p. 94. Available at https://www.sedar.com/GetFile.do?lang=EN&docClass=24&issuerNo=00032889&issuerType=03&projectNo=01866663&docId=3060129

[xii] AMC Mining Consultants Limited (2011) Technical report. Technical Report on Wafi-Golpu Property in Morobe Province Papua New Guinea. AMC 711037. p. 109. Retrieved from https://www.sedar.com/GetFile.do?lang=EN&docClass=24&issuerNo=00032889&issuerType=03&projectNo=01969005&docId=3203677

[xiii] Ibid. p. 142.

[xiv] Taylor, H.K. General background theory of cut-off grades. Transactions of the Institution of Mining and Metallurgy Section A, 1972. pp. 160-179.

[xv] Stermole Franklin, J., Stermole, John, M., & Pederson, Andrew H. (2017). Economic evaluation and investment decision methods (15th edition, p. 645). Lakewood, CO: Investment Evaluations Corporation.

[xvi] Mankins, J. C. (2017). New developments in space solar power. *NSS Space Settlement Journal,* 1(3). Retrieved from http://space.nss.org/media/NSS-JOURNAL-New-Developments-in-Space-Solar-Power.pdf. Accessed 6 June, 2018.

[xvii] John C. Mankins. “SPS-ALPHA: The First Practical Solar Power Satellite via Arbitrary Large Phased Array (A 2011-2012 NASA NIAC Phase 1 Project).” Santa Maria, CA: Artemis Innovation Management Solutions LLC. September 15, 2012. pp. 69-70, 81.

[xviii] Ibid. p. 78.

[xix] Argote, L, and Epple, D. “Learning Curves in Manufacturing.” Science., vol. 247, no. 4945, Science Co, pp. 920–24, doi:10.1126/science.247.4945.920.

[xx] Ibid.

[xxi] http://www.spacex.com/about/capabilities

[xxii] https://www.cnbc.com/2018/02/12/elon-musk-spacex-falcon-heavy-costs-150-million-at-most.html

---

[xxiii] https://docs.google.com/spreadsheets/d/17n9ynWx_04Tw5AZkgQoHItruoR1oAfhw3FkGOvtQlYk/edit#gid=1894457952. Accessed 14 July, 2018.

[xxiv] Greenblatt, J. B., 2018, "BFR economic analysis," Emerging Futures, LLC, 16 July.

[xxv] John C. Mankins. “SPS-ALPHA: The First Practical Solar Power Satellite via Arbitrary Large Phased Array (A 2011-2012 NASA NIAC Phase 1 Project).” Santa Maria, CA: Artemis Innovation Management Solutions LLC. September 15, 2012. pp. 70-71, 82.

[xxvi] https://www.scribd.com/document/217716910/SSP-Power-Star-Presentation. Accessed 27 August, 2018.

[xxvii] https://spacejournal.ohio.edu/app/generic.html. Accessed 27 August, 2018.

[xxviii] https://spacejournal.ohio.edu/issue18/sunflower.html. Accessed 28 August, 2018.

[xxix] https://www.researchgate.net/publication/286148246_SSPS-OMEGA_A_new_concentrator_system_for_SSPS. Accessed 28 August, 2018.

[xxx] https://scholarworks.iupui.edu/bitstream/handle/1805/11336/Schubert_2016_analysis.pdf?sequence=1&isAllowed=y. Accessed 28 August, 2018.

[xxxi] https://www.mtu.edu/ece/department/faculty/full-time/zekavat/pdfs/ssp-2017/ng-caltechpanel-sspi-technology-maturation-approved.pdf. Accessed 28 August, 2018.

[xxxii] https://www.mtu.edu/ece/department/faculty/full-time/zekavat/pdfs/ssp-2017/ssp2017-cassiopeia-sica-design-presentation.pdf. Accessed 28 August, 2018.

[xxxiii] Naqavi, Ali & P. Loke, Samuel & D. Kelzenberg, Michael & M. Callahan, Dennis & C. Warmann, Emily & Espinet-González, P & Vaidya, Nina & A. Roy, Tatiana & Huang, Jing-Shun & Vinogradova, Tatiana & J. Messer, Alexander & Atwater, Harry. (2017). Extremely broadband ultralight thermally emissive metasurfaces.