IAF-00-R.1.06
A Unified Economic View of Space Solar Power

A.C. Charania
J. R. Olds

Space Systems Design Laboratory
Georgia Institute of Technology
Atlanta, GA
USA

51st International Astronautical Congress
2-6 Oct. 2000
Rio de Janeiro, Brazil

IAF-00-R.1.06

A UNIFIED ECONOMIC VIEW OF SPACE SOLAR POWER (SSP)

A.C. Charania* and Dr. John R. Olds†
Space Systems Design Laboratory
School of Aerospace Engineering
Georgia Institute of Technology, Atlanta, GA 30332-0150 USA

ABSTRACT

Space Solar Power (SSP) is a concept to beam energy from space to terrestrial power grids that could be feasible in about twenty to forty years. Due to the current climate of limited government funding for such large-scale space projects, NASA would prefer more industry involvement (technically and more important financially) in SSP. This study seeks to offer a unified economic view of SSP by examining the breadth of the SSP business case, from the development of the infrastructure (the actual SSP satellites) to on-orbit delivery. The indigenously developed Space Solar Power Abbreviated Economics (SSPATE) model is used to establish financial relationships between: 1.) the prices distinct Earth-to-orbit (ETO) and in-space transportation companies charge to a hypothetical company building Solar Power Satellites (SPS); and 2.) the financial metrics (Net-Present-Value, Internal Rate of Return, etc.) that can merit a legitimate business case for all three ventures. Deterministic and probabilistic models reveal that inherent trade-offs exist in either making the transportation companies (an ETO Inc. and In-Space Inc.) or infrastructure company (SSP Inc.) viable. Major reductions in SSP launch mass (even at the same cost as larger systems) is seen as one of the main mechanisms to alleviate this imbalance.

* - *Graduate Research Assistant, School of Aerospace Engineering, Student Member AIAA.*
† - *Assistant Professor, School of Aerospace Engineering, Senior Member AIAA.*

NOMENCLATURE

CABAM	Cost and Business Assessment Module
DDT&E	Design, Development, Testing, and Evaluation
DSM	Design Structure Matrix
ETO	Earth-to-Orbit
GEO	Geostationary Earth Orbit
INSINCM	In-Space Incorporated Model
IOC	Initial Operability Capability
IRR	Internal Rate of Return
NPV	Net Present Value
RLV	Reusable Launch Vehicle
SPS	Solar Power Satellite
SSP	Space Solar Power
SSPATE	Space Solar Power Abbreviated Transportation Economics
SSTO	Single Stage to Orbit
TFU	Theoretical First Unit

INTRODUCTION

Space Solar Power (SSP) is a concept to beam energy from space to terrestrial power grids that could be feasible in about twenty to forty years. In theory, due to negligible atmospheric losses, power generation from a solar cell in space is nine times as efficient as one on the ground. Space Solar Power would harness these efficiencies through technologies such as microwave wireless power transmission (WPT) to large (several kilometers in diameter) terrestrial rectifying antennas (rectennas) for eventual dispersion into the power grids of the world. A current sample SSP architecture incarnation, the Geostationary Earth Orbit (GEO) SunTower, in order to deliver about 1.2 GW of power to a terrestrial electrical grid, has a total system mass of over 20,000 MT (equivalent to more than 40 International Space Stations) with the requirement of lasting over 30 years in orbit.

Each SPS would have its operational life be in GEO and be constructed from smaller pieces typically delivered from Low Earth Orbit (LEO). A dual phase transportation system emerges from this scenario, namely separate Earth-to-Orbit and in-space transportation modes. In this envisioned scenario, an RLV delivers a 20-40 MT piece of the SPS to LEO which is either sent directly with the in-space "tug" to the final orbit in GEO or aggregated with previously delivered RLV pieces into a "wagon train" in-space transportation system to GEO. This delivery schedule would be kept in order to assemble one SPS in orbit for over 30 years.

Space Solar Power has been under study by the National Aeronautics and Space Administration (NASA) for the past several years. Due to the current climate of limited government funding for such large-scale space projects, NASA would prefer more industry involvement (technically and more important financially) in SSP.

Previous studies by the Futron Corporation (Bethesda, MD USA) have examined the economic viability of a commercial enterprise that owns the SSP infrastructure[1,2, 3]. Previous studies by the Space Systems Design Lab (SSDL) have examined the impact of this commercial venture on two commercial transportation enterprises: an Earth-to-orbit reusable launch vehicle (RLV) company and an in-space transportation company[4].

OBJECTIVE

This study seeks to examine the economic and financial relationships between all three economic entities: a company which owns the SSP infrastructure (a so-called SSP, Inc.), a company which uses RLVs to launch these payloads (a so-called ETO, Inc.), and a company which delivers these infrastructure payloads to their final orbital destinations (a so-called In-Space, Inc.).

Various combinations of SSP system architectures, RLVs, and in-space transport options are examined in order to determine whether SSP is economically viable. This viability is dependent on whether there are transportation companies in existence that can make financial profit from delivering SSP infrastructure cargo to a final beaming orbit. Simultaneously, the SSP infrastructure company financials must also be viable. This study seeks to offer such a unified economic view of SSP by examining the breadth of the SSP business case, from the development of the infrastructure (the actual SSP satellites) to on-orbit delivery.

Previous studies by the SSDL have indicated that for prices of around $400/kg, a company building an RLV for SSP obtains IRRs in excess of 20%. Furthermore, a company providing in-space transportation services needs to charge in the thousands of dollars per kg for IRRs greater than 20%. This price fluctuates (from one thousand to more than five thousand dollars) depending upon the particular in-space transportation concept such as solar electric propulsion (SEP), solar thermal propulsion (STR), tether, or nuclear thermal rocket (NTR). These prices for this second phase of transport (from LEO to GEO) are normally higher than the RLV provider charges to SSP infrastructure company for the first phase delivery to LEO.

Initial indications are that it is very difficult for the SSP infrastructure company (SSP Inc.) to perform well financially for the above transportation costs (ETO and in-space). It was envisaged that if the two transportation companies were to lower prices to SSP Inc. then all three companies would become financially viable. Firstly, SSP Inc.'s transportation costs could be reduced. This can be substantial since transportation costs can account for more than one half of the total life cycle cost of the SSP system, depending upon the particular architecture. Additionally, since the two transportation companies have relatively higher IRRs (above 20%) than SSP Inc., a reduction in price would lower revenues (and thus IRR) but still keep the programs viable.

The first phase of this investigation examined the benefits of a financial trade-off between three companies. Specifically, can a trade off be made by an absolute reduction in the IRRs of the transportation companies in order to increase the IRRs of the much lower performing SSP infrastructure company? These trade-offs were performed through a pure manipulation of prices to transfer the financial benefits of the transportation companies to the SSP infrastructure company.

Both technical and commercial uncertainties are inherent in the Space Solar Power concept. In addition to the above direct manipulation of prices, a probabilistic approach was taken to the effects of pricing schemes between these three companies (one infrastructure and two transportation) on each company's IRR. This second phase of the investigation used triangular uncertainty distributions on prices the companies charged to each other as well as on the costs and masses of each system[5].

IMPLEMENTATION

The relationships between these companies (SSP Inc., ETO Inc., and In-Space Inc.) was modeled using three company specific MS Excel spreadsheets aggregated together in the Space Solar Power Abbreviated Economics (SSPATE) model. The model requires mass and cost inputs for each company's product (whether they be vehicles or SSP infrastructure).

The SSPATE model is based upon two transportation models derived at the SSDL. This includes the Cost and Business Analysis Module (CABAM) used for ETO RLV economic analysis. The other model used was the In-Space Incorporated Model (INSINCM) used for in-space transportation economic assessments. Both models were either originally developed or enhanced by the authors. A general-purpose economics model for the actual SSP infrastructure company was developed exclusively for this analysis. All three company models in the SSPATE model are not meant as representations of the full design process for each system, but "abbreviated" versions with limitations on market elasticities for power demand, financing schemes, acquisition schedules, etc. Figures 1 and 2 detail the interrelationships in the SSPATE model between the infrastructure and transportation companies. The main input/output of the SSPATE model is in the form of a pricing mechanism sheet. The controllable prices are (in $/kg):

- I: Price Charged by ETO Inc. to SSP Inc.
- II: Price Charged by In-Space Inc. to SSP Inc.
- III: Price Charged by ETO Inc. to In-Space Inc.

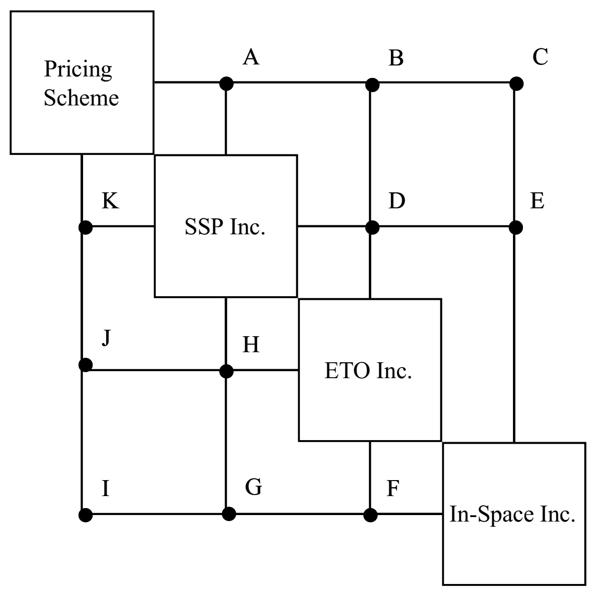

Figure 1. SSPATE Model Design Structure Matrix

Feed Forward Links

A: SSP Program Specific Market Pricing
Primary and Niche Markets and Capture %
Price and Externality Costs [$/kW-hr]

Price I: Price Charged by ETO Inc. to SSP Inc. [$/kg]
Price II: Price Charged by In-Space Inc. to SSP Inc. [$/kg]

B: Price I: Price Charged by ETO Inc. to SSP Inc. [$/kg]
Price III: Price Charged by ETO Inc. to In-Space Inc. [$/kg]

C: Price II: Price Charged by In-Space Inc. to SSP Inc. [$/kg]
Price III: Price Charged by ETO Inc. to In-Space Inc. [$/kg]

D: SSP Inc. Launch Mass Per Year [MT]

E: SSP Inc. Launch Mass Per Year [MT]

Feedback Links

F: In-Space Inc. Required ETO Launches

G: In-Space Transportation Cost For SSP Inc. [$B]

H: ETO Transportation Cost for SSP Inc. [$B]

I: In-Space Inc. Financial Metrics
IRR, NPV, ROI, Revenue, Total LCC Incurred (w/ and w/o financing)

J: ETO Inc. Financial Metrics
IRR, NPV, ROI, Revenue, Total LCC Incurred (w/ and w/o financing)

K: SSP Inc. Financial Metrics
IRR, NPV, ROI, Revenue, Total LCC Incurred (w/ and w/o financing)

Figure 2. SSPATE Model
Design Structure Matrix Legend

SSPATE: SSP Economics

A simplified economics model of the SSP infrastructure company was developed for this investigation. The SSP infrastructure company was assumed to be responsible for the development of the power satellites, contracting out launch services to separate companies.

The various stages of the program were deconstructed into four phases:

1. Space Segment: that portion of the system to be transported into space for power generation and transmission through the atmosphere.

2. Ground segment: that portion of the system on the Earth's surface used for receiving power from space and distribution to terrestrial power grids.

3. Space Launch: portion of the system required for integration of the space segment with the ETO space transportation vehicle.

4. In-Space Launch: portion of the system required for integration of the space segment with the in-space transportation vehicle.

The modeling effort for the SSP infrastructure company also included equity calculations, debt scheduling, depreciation, income statements, and free cash flow calculations.

SSPATE: RLV Economics

The RLV economics portion of the SSPATE model is based upon CABAM (Cost and Business Analysis Module), a conceptual vehicle level financial assessment tool. CABAM focuses on both the cost attributes and potential revenue streams of conceptual RLV projects. CABAM delivers various evaluation metrics including net present value (NPV), internal rate of return (IRR), and return on investment (ROI).

CABAM uses data from the NASA Commercial Space Transportation Study (CSTS) and user entered competition models to approximate the price elastic behavior of potential markets[6]. Costs in CABAM are derived from vehicle subsystem masses processed through NASA- Air Force Cost model (NAFCOM). Total Life Cycle Costs (LCC) and IRR are estimated based upon project cash flows[7].

SSPATE: In-Space Transportation Economics

Given the commercial nature of the SSP infrastructure program, a similar worldview was adopted in the economic modeling for the space transportation segment. Comparable to the modeling of a commercial provider of ETO launch services in CABAM, a commercial in-space transportation provider is modeled in the SSDL in-house tool INSINCM (In-Space Incorporated Model).

INSINCM builds a vehicle development program around projected SSP infrastructure demand. The financial qualities of that program are determined from user defined programmatic variables. The company that is building the in-space transportation vehicle is not assumed to be the same as the provider of ETO launch services. There is a separate company acting as the sole provider of in-space launch services from an initial transfer orbit to a final destination orbit for each piece of the SSP infrastructure that fits within the ETO vehicle. Thus the commercial provider of in-space transportation services modeled in INSINCM is assumed to be using the same ETO launch service provider as the SSP infrastructure company. In order to account for the cost of launching the in-space transportation system INSINCM requires the payload capability and ETO launch price from the ETO economics portion of the SSPATE model.

INSINCM does not have the capability to cost concepts given a particular vehicle definition. The costs in the model come from other sources (such as from literature reviews or cost estimating relationships). These costs are integrated into the INSINCM financial engine in order to determine the full financial scope of the project. INSINCM is robust enough to handle different vehicle concepts, development schemes, financing plans, and pricing structures. The model can also scale up the required number of in-space vehicles depending upon the payload to be delivered to any final SSP destination orbit.

The economic and financial portions of the INSINCM model obtain inputs from the market, schedule and economic, and vehicle definition sections of the model (see Figure 3). Financial metrics like internal rate of return (IRR) and net present value (NPV) are determined through calculation of specific program costs coupled with user-defined pricing. Thus there is no elastic market for demand specified in the model. The SSP infrastructure company is assumed to pay the in-space transportation company a set price ($/kg) for its services.

The model can handle up to a three-stage transportation vehicle. For each stage of the vehicle the following fleet definition variables are needed: system dry mass w/o payload, total propellant mass, payload capability of module, payload inefficiency factor, overall reliability, trip time to delivery orbit (days), in space turn-around-time (days), average annual salary per man ($/yr), manpower per launch, labor cost per year ($M/yr), fleet lifetime (maximum number of reuses per year), expended hardware/launch (% dry mass w/o prop.), expended hardware/launch, hardware refurbishments ($/kg reusable), propellant costs ($/kg), DDT&E cost, TFU cost, learning effects, and government contribution percentages.

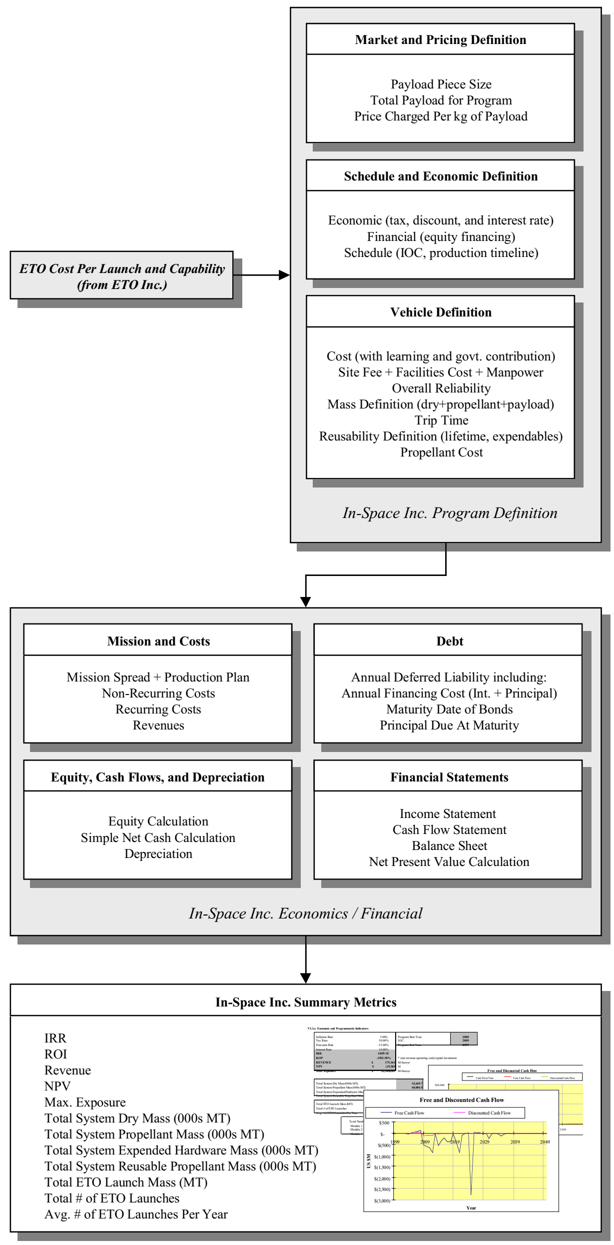

Figure 3. SSPATE: In-Space Inc. Economics

A separate mission and costs section determines the spread of flights dependent upon the payload to be delivered per year. The payload capability and reusability data of the in-space transportation vehicle determines the actual trips per year, number of vehicles for such trips, the number of refurbished vehicles, the total dry mass required, the total propellant mass required, the total expended hardware mass, and the new propellant mass required. These are aggregated to determine the total number of ETO flights per year. This data is then used to determine non-recurring costs (vehicle and facilities development and government contribution), recurring costs (site fee, insurance, labor cost, propellant cost, hardware + propellant refurbishment), ETO launch costs, and revenues (for an input price).

Equity calculations are then determined along with associated deprecation schedules. Deprecation is defined using U.S. government standards based upon a 5-year deprecation of fixed assets. A separate debt calculation is made with the assumption that negative cash flows in any given year (after accounting for revenue and equity infusion) are paid off using either long or short-term bonds (20, 15, 10, 5, or 1 year varieties). All the above information is aggregated to obtain the discounted cash flows and associated summary metrics like NPV (for NPV, based upon user defined discount rates).

SSPATE Model Assumptions

The envisioned future for these companies was set in the beginning of the next decade. Development would take the rest of the next decade with the first set of launches to begin in 2020 (see Table 1). The SSP infrastructure project was considered more riskier than either of the transportation projects (thus it was given a higher discount rate). Government backing of loans was only considered for the transportation companies with the SSP infrastructure project obtaining greater equity financing.

Table 1. Financial Modeling Assumptions

Financial Parameter	SSP Inc.	ETO Inc.	In-Space Inc.
Program Start Year	2012	2012	2012
Program End Year	2050	2050	2050
IOC	2020	2020	2020
Real Discount Rate [%]	40	30	30
Interest Rate [%]	10	7.5	7.5
Initial Capital + Equity [$B]	10	4	4

Additional assumptions include:

1. Already existing transportation and infrastructure concepts were inserted into the SSPATE model.

2. An SSP representative concept was developed from a 20,000 MT GEO SunTower delivering 1.2 GW of power to the ground. As detailed in Table 2, system costs were broken out into four categories (space segment, ground segment, space launch, and in-space launch) into four cost grouping each (DDT&E, TFU, facilities, and operations). These costs came from review of literature and assumptions about technology development.

Table 2. System Costs for Representative GEO SunTower

Per Each SPS	DDT&E ($B)	TFU ($B)	Facilities ($B)	Yearly Ops ($B)
Space Segment	10	7	6	1
Ground Segment	4	0.7	4	0.5
Ground Launch	2	0	2	0.5
In-Space Launch	2	0	2	0.5

The power delivered by each SSP SunTower was 1.2 GW. Both additional efficiency losses to customers and losses due to duty cycle for each SPS were taken into account (both set at 80%). It was assumed that each year 5% of the total SPS mass would need to be refurbished.

Two different markets were assumed for the power emanating from the SSP system. A primary market akin to the base load power market was assumed. A secondary, niche market akin to the peak power market was also modeled. The price in the niche market was set to 1.5 times the price in the primary market. It was specified that 60% of the power from each SPS would be sold to primary markets and the rest to niche markets.

The only government contribution to the SSP project was in the form of demonstration projects that were assumed to cost 1-3% of the total development cost.

3. The representative ETO vehicle is the SSDL derived Argus, a rocket-based combined-cycle (RBCC) single-stage-to-orbit (SSTO) launch vehicle utilizing a Maglev sled and track system to accelerate it to Mach 0.8 for horizontal liftoff[4]. Advanced subsystem and material technologies are used throughout on the vehicle. The payload capability of this vehicle is 50,000 lbs (22,727 kg) to a LEO equivalent orbit inclined at 28.5 degrees. It was assumed that this vehicle would also fly IRR maximizing captured payloads from CSTS derived market elasticities.

   Assumptions set up in ETO economics section for this examination include: government offset of 20% of the airframe and 100% of the development costs (but none of the production), a constant source of revenue from SSP for payload delivered, low interest rate, and government-backed loan rates of 7.5%. Since so many vehicles are required to meet SSP launch demand, the acquisition costs of all the vehicles required are amortized over a 10-year period.

4. The representative in-space transportation vehicle is an SSDL derived non-reusable solar electric propulsion (SEP) orbital transfer vehicle (OTV) with a payload capability of over 120 MT[4]. The vehicle uses Xenon for its SEP engines and is carried into space by the same ETO vehicle that carries SSP infrastructure material for delivery.

Uncertainty Analysis

Tables 3, 4, 5, and 6 list the uncertainty distributions placed upon the Pricing Scheme, SSP Inc., ETO Inc., and In-Space Inc. portions of the SSPATE model respectively. Distributions were placed generally upon three categories of items: prices, system costs, and system masses.

Table 3. Triangular Uncertainty Distributions for Pricing Scheme Portion of SSPATE Model

Item	Minimum Value	Most Likely Value	Maximum Value
Price I [$/kg]	100	1,280	5,000
Price II [$/kg]	500	4,054	5,000
Price III [$/kg]	500	2,000	5,000
Primary Market Price [$/kW-hr]	0.05	0.05	0.10
Cost of Externality* [$/kW-hr]	0.10	0.20	0.30

Note: * Added in order to compare solar power to other energy sources on an equivalent economic and environmental basis (non-polluting energy would be worth more than polluting)

Table 4. Triangular Uncertainty Distributions for SSP Economics Portion of SSPATE Model

Item	Minimum Value	Most Likely Value	Maximum Value
Launch Mass on one (1) SPS [MT]	15,000	20,000	25,000
Refurbishment % of Total SPS Mass Per Year	2%	5%	10%
DDT&E Cost of SSP Space Segment [$B]	3	10	20
TFU Cost of SPS [$B]	3	7	10
Facilities Cost for all SPSs [$B]	2	6	8
Yearly Operations Cost for all SPS [$B]	0.5	1	2
Duty Cycle [%]	60	80	90

Table 5. Triangular Uncertainty Distributions for ETO Economics Portion of SSPATE Model±

Item	Minimum Value	Most Likely Value	Maximum Value
Site Fee per launch [$M/launch]	0.20	0.25	0.50
Labor Cost per launch [$M/launch]	0.20	0.25	0.50

±Note: Also Includes +/- 10% distributions on ETO vehicle weights

Table 6. Triangular Uncertainty Distributions for In-Space Economics Portion of SSPATE Model

Item	Minimum Value	Most Likely Value	Maximum Value
DDT&E Cost [$M]	600	773	1000
TFU Cost [$M]	250	369	500
Xenon Propellant Cost [$/.kg]	72	144	288
Facilities Cost [$M]	100	400	500
Site Fee per launch [$/launch]	0.20	0.25	0.50
Labor Cost per launch [$/launch]	0.20	0.25	0.50

RESULTS

As stated previously the total LCC, and subsequently IRR, of the SSP infrastructure company is dependent upon transportation costs. Figure 4 gives the proportion of total LCC accounted for by launch costs given the previously mentioned assumptions on SPS unit cost and mass using most likely values for the model parameters. For the first phase of the investigation, transportation prices were reduced in order to gauge the effect on the SSP infrastructure company's IRR. One assumption throughout this deterministic portion of this examination is that an environmental externality cost of $0.10-$0.30 /kW-hr is being added to any mentioned price that the SSP infrastructure is charging to its power customers (see Table 3). Supposedly in an environmental conscious future, consumers will be willing to pay more for cleaner forms of energy. This extra willingness to pay reflects the externality costs associated with polluting energy sources

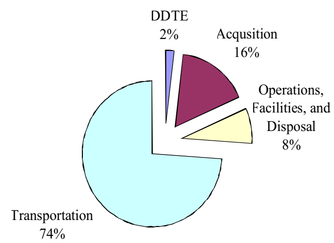

Figure 4. SSP System Cost Breakdown (Most Likely Values)

Deterministic Results

Keeping the prices (Prices I and II) charged by both transportation companies to SSP Inc. the same, a linear equation results for the IRR of the SSP infrastructure company. The equation for this IRR, based upon an input transportation price in $/kg is:

$$IRR_{SSPInc.} = -0.0001672 * \text{ Price} + 0.0700431 \quad (1)$$

With an associated $R^2 = 0.9990401$

The above equation was gathered by keeping the price between $10/kg and $300/kg. Examination of the data indicates that SSP Inc. cannot make a reasonable IRR (>10%) even with launch low launch prices. At $10/kg launch price (for both ETO and in-space), the IRR for SSP Inc. is approximately 6.8%.

An alternate analysis was performed in which the launch mass of each SPS was reduced by half to approximately 10,000 MT. Total development, acquisition, and operations costs remained the same (thus the $/kg cost to deploy the system went up). Sweeps of prices SSP Inc. has to charge to obtain various IRRs indicate that 10,000 MT SPS cases normally have IRRs up to 8% higher (in absolute terms) than the 20,000 MT per SPS case (see Figure 5).

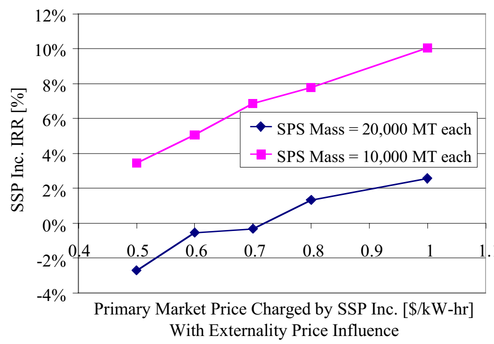

Figure 5. IRR Price Sweep for Different SPS Launch Masses (a $0.20/kW-hr externality charge is added to the above listed prices to obtain IRRs)

The prices an SSP infrastructure company has to charge in order to become financially viable appears to be over $0.50/kW-hr. This is extremely high given current U.S. energy production costs at less than $0.05/kW-hr. The modeling effort here did not take into account dynamic competition effects expect for pricing given pollution externality costs for other energy sources.

Stochastic Results

The second phase of this examination, the uncertainty formulations, placed less discretion upon price manipulation as a user controlled input. Price was viewed, along with cost and mass, as another variable with nominal ranges of certainty. Table 7 lists the summary statistics for each of the three companies in the study. It should be noted that not every Monte Carlo run netted positive IRRs.

Results indicate that for over 7000 Monte Carlo simulations only 3 runs made the SSP infrastructure company return a positive IRR. Only 1,971 runs had positive IRRs for the in-space transportation company. Exactly 6,521 runs returned positive IRRs for the ETO transportation company. Mean values for IRR for the two transportation companies were greater than 30%. The reward to risk ratio (mean$_{IRR}$ / σ_{IRR}) for both transportation companies is low, between 1.7 and 2.6. With a 95% confidence level, the IRR of the ETO company is at least or greater than 12.4%. At the same confidence level, the IRR for the in-space transportation company is at least or greater than 6.8%.

Table 7. Statistics from Monte Carlo Simulation

Statistics	IRR: SSP Inc.	IRR: ETO Inc.	IRR: In-Space Inc.
Positive IRR Trials (out of 7010 Monte Carlo Runs)	8 (0.1%)	6,521 (92.5%)	1,971 (28.1%)
Mean	0.8%	31.5%	36.4%
Standard Deviation	1.0%	11.9%	21.4%
Coeff. of Variability	1.19	0.38	0.59
Range Minimum	0.1%	0.1%	4.7%
Range Maximum	1.9%	60.9%	91.6%

In-Space Inc.'s higher standard deviation negates its higher mean value for IRR when compared to ETO Inc. There is more uncertainty for the in-space company than the ETO transportation company. Examination of the distributions shows a skewed nature to the IRR of the in-space transportation company towards a lower value for IRR (see Figure 6 and 7). Many of the Monte Carlo simulations resulted in formulaic errors for IRR calculation given overwhelming negative cash flows in each year. It was decided to spotlight only the positive IRR values. The distributions illustrate only those runs with positive IRRs, showing the most optimistic of results (resulting in the skewed distribution in Figure 7). Figures 8, 9, and 10 give the cumulative probability distributions of Net Present Value (NPV) for SSP Inc., ETO Inc., and In-Space Inc. (for the associated real discount rates shown in Table 1). Unlike the IRR distributions, these show results for all the trials since the mathematical errors in finding zero roots is not present for the NPV calculation versus the IRR calculation. The 80% confidence levels for all three company NPVs are negative. Only ETO Inc. has a positive mean NPV value.

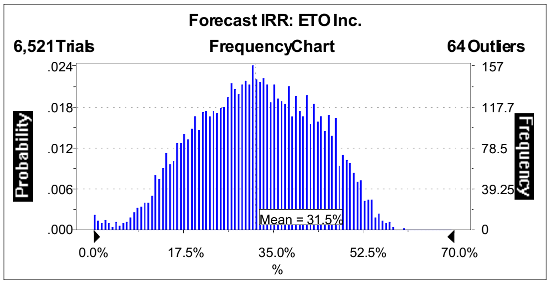

Figure 6. IRR Frequency Dist.: ETO Inc.
(Positive IRRs only)

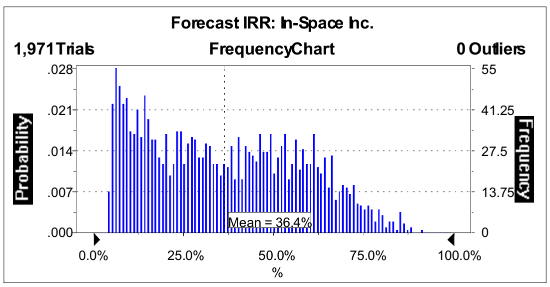

Figure 7. IRR Frequency Dist.: In-Space Inc.
(Positive IRRs only)

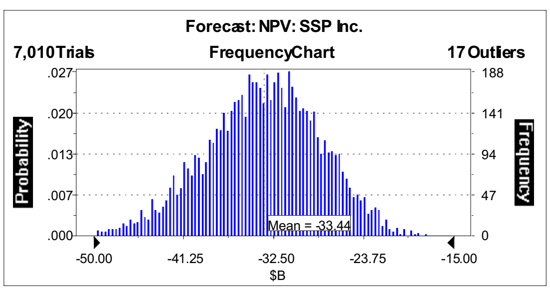

Figure 8. NPV Frequency Dist.: SSP Inc.

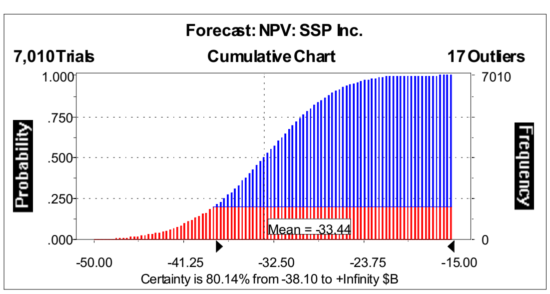

Figure 9. NPV Cumulative Dist.: SSP Inc.

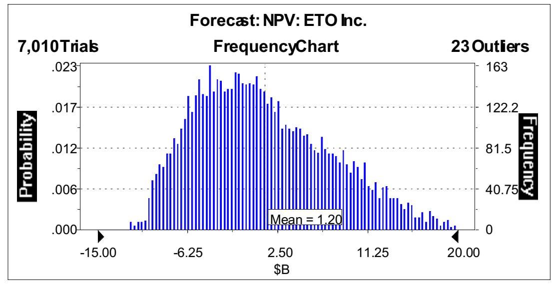

Figure 10. NPV Frequency Dist.: ETO Inc

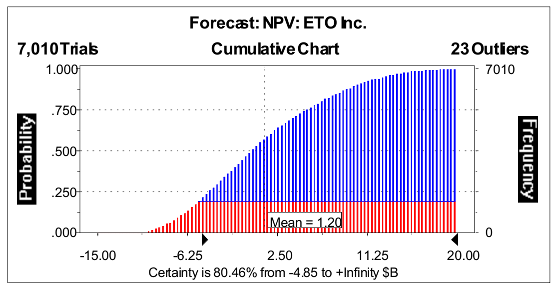

Figure 11. NPV Cumulative Dist.: ETO Inc.

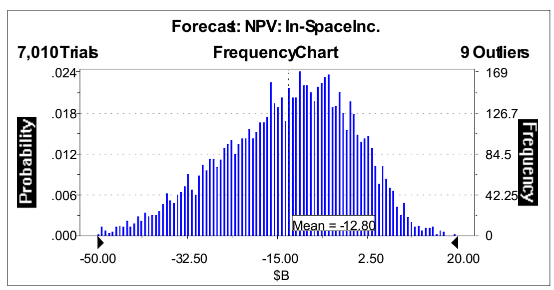

Figure 12. NPV Frequency Dist.: In-Space Inc.

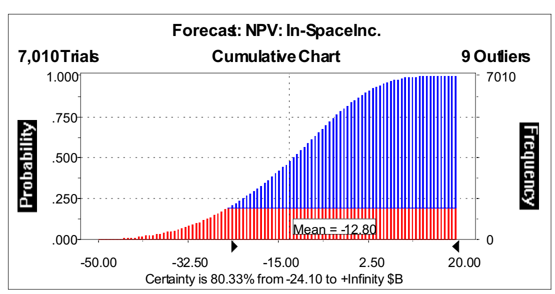

Figure 13. NPV Cumulative Dist.: In-Space Inc.

CONCLUSIONS

A new model named the Space Solar Power Abbreviated Economics (SSPATE) model has been developed to attempt a unified view of the economics of the SSP problem: from infrastructure to transportation. The results indicate that for a valid set of proposed SSP architectures, the SSP infrastructure company is struggling to make positive IRRs greater than 10% if prices for power are not an order of magnitude greater than current power generation prices. Reduction of launch mass per SPS by 50% does help achieve positive IRRs sooner with lower prices for power. Transportation prices have to be so low for the SSP infrastructure company to make positive IRRs (below $100/kg), that neither transportation company can make adequate financial returns. Obviously the conclusions reached are dependent upon the input concepts used (namely a 20,000 MT 1.2 GW SunTower, Argus SSTO launch vehicle, and SEP transfer vehicle). However, the purpose of this examination was to show the usefulness of the SSPATE model and some indication of future direction on the part of SSP analysts. Future work could consist of using different system concepts, elastic power market definitions, alternative price sweeps, and coupling of the probabilistic methods with response surface methods.

REFERENCES

1. Feingold, Harvey, et al. Space Solar Power: A Fresh Look at the Feasibility of Generating Solar Power in Space for Use on Earth, Science Applications International Corporation, April 4, 1997, Schaumburg, Illinois, SAIC-97/1005.

2. Feingold, Harvey, et al. Space Solar Power: 1998 Concept Definition Study, Science Applications International Corporation, February 1999, SAIC-99/1016.

3. Howell, Joe. Early, Preliminary, Partial Report: Space Solar Power Concept Definition Study. Huntsville, Alabama: Marshall Space Flight Center, 1998.

4. Olds, J., Way, D., Charania, A., Budianto, I., Marcus, L., "In-Space Deployment Options for Large Space Solar Power Satellites," IAA-00-R.2.02, 51st International Astronautical Congress, Rio de Janeiro, Brazil, October 2-6, 2000.

5. Whitfield, J. A. and Olds, J. R., "Economic Uncertainty of Weight and Market Parameters for Advanced Space Launch Vehicles," AIAA 98-5179, 1998 Defense and Civil Space Programs Conference and Exhibit, Huntsville, AL, October 28-30, 1998.

6. Commercial Space Transportation Study Final Report, Boeing, General Dynamics, Lockheed, Martin Marietta, McDonnell Douglas and Rockwell, pp. 198-229, April 1994.

7. Lee, H. and Olds, J. R., "Integration of Cost and Business Simulation into Conceptual Launch Vehicle Design," AIAA 97-3911, 1997 Defense and Space Programs Conference and Exhibit, Huntsville, AL, September 1997.