Operational Demonstration of Space Solar Power (SSP): Economic Analysis of a First Revenue Satellite (FRS)

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Niche markets (military installations, developing nation remote power, etc.) may be potential markets where Space Solar Power (SSP) satellites may be economically viable, given certain government support and Earth-to-Orbit launch cost assumptions. An operational demonstrator could be one approach for those markets. This paper examines such a concept, referred to by the authors as the SSP First Revenue Satellite (FRS). The FRS would be a mid-power (1-20 MW of delivered power) space-to-ground demonstrator of SSP. The purpose would be two-fold, prove the end-to-end technical capability and then demonstrate operations over multiple years. The FRS system would be turned over to commercial operators for public/private service. This is deemed to be a more feasible and useful mid-scale demonstration of SSP. This would be a hybrid public-private system consisting of low number of satellite systems. A notional SSP architecture is taken as a case study for this examination. Economic analysis is performed to look at the output prices such a venture would charge based upon various financing options. The objective of this analysis is to determine whether the FRS can be a commercially viable pathway for a SSP demonstrator.

Key Words: space, solar, power, economics, energy

Nomenclature

CABAM	:	cost and business analysis module
FRS	:	first revenue satellite
SSP	:	space solar power

1. Introduction

1.1. Overview

This paper is an effort to provide a glimpse of the economics involved in a harnessing energy from space. 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 (see Fig. 1).

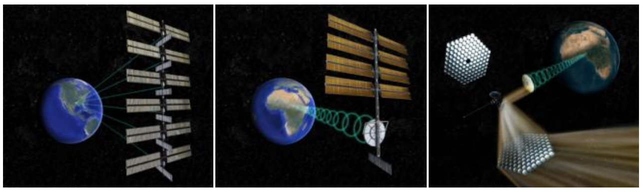

Fig. 1. Notional representations of large scale Space Solar Power (SSP) systems in GEO: Provided for 2010-2011 IAA Space Solar Power Study (Illustration source: SpaceWorks).

The viability of Space Solar Power (SSP) to compete and supply electricity for consumption on the Earth has been debated for quite some time[1,2,3,4,5,6,7]. Some of the authors have previously performed analysis of overall SSP systems including space transportation and economic issues, specifically including a top level economic analysis for a notional Space Solar Power company (full up system) and analyzing breakouts between space transportation costs and all other costs (terrestrial markets)[8]. This also consisted of a global electricity price analysis including niche customer analysis (humanitarian, remote sites, military, etc.) to determine price points and quantity/schedule of demand. Most recently the authors examined previous SSP economic studies[9]. Past projects worked on by the authors include the NASA Fresh Look studies and SERT studies as well as the recent 2010 International Academy of Astronautics (IAA) study on SSP. The analysis here focuses on the concept of a SSP First Revenue Satellite (FRS) and its associated economic analysis. This would be a hybrid public-private system with an interim 1-2 satellite system. SpaceWorks recently started thinking about the merits of such a system and present here simulation updates and refined conclusions from previous work[10].

The objective of this analysis is to provide some basis to determine whether SSP can be commercially viable and pathways for such commercialization. The specific approach is discussion of the FRS satellite concept.

After many analyses performed by the authors over the years, it appears from qualitative and quantitative assessments that a fully commercially financed, large-scale (GWs of power delivered to the ground) SSP system may not be viable in current energy markets. However, SSP projects could be joint public-private developments, similar to infrastructure projects.

For such projects, the actual demonstration of operations for a long time period to potential consumers of energy is just as important as the end-to-end (space-to-ground) demonstration.

The authors here then suggest the philosophical concept of a SSP First Revenue Satellite (FRS). The SSP First Revenue Satellite (FRS) is a potential better model for sustainable SSP development. Advocates of SSP advocate medium level (MWs of power delivered) demonstrators in their roadmaps for SSP development. The FRS would be a mid-power (~1-20 MW) space-to-ground demonstrator of SSP. The purpose would be two-fold, demonstrate the end-to-end capability and then demonstrate operations (multiple years after the demonstration phase). After the initial end-to-end demonstration phase the system would be turned over to commercial operators for public/private service. This is deemed to be a more feasible and useful mid-scale demonstration of SSP.

1.2. Global Niche Markets

As a background to the First Revenue Satellite (FRS) analysis it may be illuminating to examine the landscape for prices and potential niche markets. Fig. 2 illustrates an incomplete but illustrative snapshot of global energy prices. Household and industry prices for baseload energy are in the tens of US cents per kilowatt hour. In developing nations the baseload price may be higher, but sometimes not necessarily. Fig. 3 takes a more detailed comparative assessment of prices on the African continent compared with US average prices. Even in Africa, it is not necessarily the case, that on average, prices are higher than the United States.

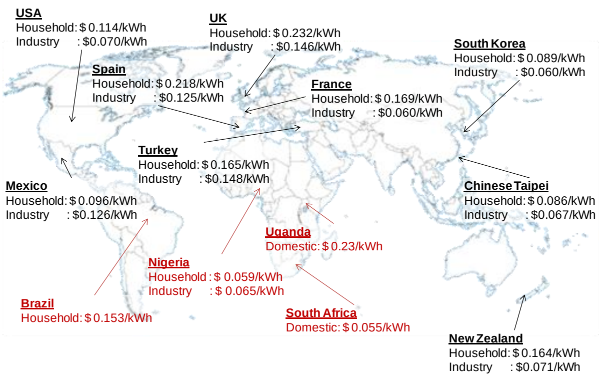

Fig. 2. Global Electricity Retail Price (2009, 1Q)[11]

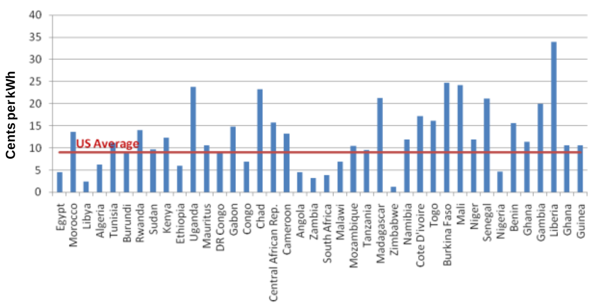

Fig. 3. Electricity Retail Price in Africa (2009)[12]

It may be the case that specific parts of countries need to be more thoroughly examined for niche markets where prices are higher and where SSP may find an application. Thus more specific case studies on particular customers, such as universities in Nigeria versus the entire country as a whole, may need to be examined.

In the search for niche markets (where prices are higher), there is interest in looking at military users, specifically the US military. Given the global nature of the US military and its operation at multiple overseas locations (many of them in potential niche market countries), they may be a potential consumer of SSP services. At many of these installations power is supplied by diesel generators. For instance one case study of such a niche customer would be Camp Lemonnier in Djibouti. This camp is a United States military installation supporting its Africa Command. This base has grown over the last two decades and is an important strategic and tactical base from which the United States can operate in Africa. Six 1500 kW electrical generators were delivered in 2007 in order to accommodate the growing power needs of this expanding base, now currently at 2 km^2 in square area (see Fig. 4)[13,14]. In June 2008, as one snapshot, more than 333,000 gallons of fuel were consumed for base support in that month alone. Separately, fuel for air operations was over 400,000 gallons during that month.

Fig. 4. Images of United States Africa Command Base Camp Lemonnier in Djibouti (and power generator installation in 2007).[13,14]

Fig. 5 shows the fuel consumption and estimates of electrical power required at several US bases overseas, ranging from East Africa (including Camp Lemonnier) to Afghanistan. The overall power level at these locations fall into the range of mid-term SSP demonstrators in the 1-20 MW range. Camp Lemonnier is not even one of the larger examples of an energy consuming niche customer for energy for the United States military if one looks at other forward deployed bases in Iraq or Afghanistan.

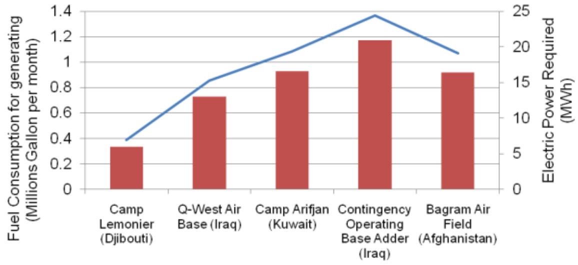

Fig. 5. Power Required For US Forces in Forward-Deployed Regions. Note: Electric power required is calculated using fuel consumption of 4 gallon/hour for a 60 kilowatt generator.[15]

There is general agreement that the fully encumbered price for energy for the US military at such installations is higher than the baseload price, even in those developing nations. This is many times due to the security requirements for such energy (i.e. security for transportation of diesel within various parts of Iraq/Afghanistan and then security for the actual power generation facilities). Many forward bases rely on electrical generators using externally delivered fuel. A single typical 60-kilowatt generator at such bases burns 4-5 gallons per hour. There are various estimates for the cost of this fuel (fully encumbered including all the transportation and security costs). Specific point values researched are displayed in Table 1. Specific, researched values for energy are in the US$1/kWh range. For instance, the National Security Space Office (NSSO) within the US Department of Defense (DoD) has stated that "When all indirect and support costs are included, it is estimated that the DoD currently spends over $1 per kilowatt hour for electrical power delivered to troops in forward military bases in war regions."[16] As an example, using estimates of around $14/gallon for delivered fuel (fully encumbered cost including transport and security) for Camp Lemonnier, this would yield an estimated $1.05 / KWh in base energy costs (based upon the monthly consumption estimate from June 2008 given earlier).

Table 1. Estimates of Fully Encumbered Fuel and Energy Costs for US Military at Forward Operating Sites (Assume Use of Terrestrial Generators)[17, 18, 19]

Source	US$/gallon	US$/ kWh
Iraq	$13.80 / gal	$0.92 / kWh
Afghanistan	$17.44 / gal	$1.16 / kWh
Heliosat	$200.00 / gal	$13.3 / kWh
Tauri Group	$400.00 / gal	$26.7 / kWh
Camp Lemonnier*	$13.80 / gal	$1.05 / kWh

Note: *Camp Lemonnier estimate calculated by SpaceWorks for the same fuel cost as that of Iraq listed in the table above.

1.3. Power Financing

When one looks at Space Solar Power (SSP) and the overall economic viability of the venture, it may be instructive to look at terrestrial analogies. These specifically include other energy projects and how they are financed. Tables 2-5 showcase four example energy projects and the breakout of financing packages for those projects. The components of financing, even though varying wildly, included some combination of commercial financing and government financing. Thus if SSP is positioned as an infrastructure investment from the outset, additional financing options can emerge. Infrastructure projects such as the conventional energy projects listed here should be used as case studies in financing for SSP advocates.

Table 2. Case Study 1: Uganda - Energy for Rural Transformation Apl-2

Case Study Overview

Organization	The government of Republic of Uganda
Region	Uganda (2009 ~ 2013)
Purpose	To increase access to energy in rural Uganda, rural energy infrastructure (electricity distribution). small scale renewable energy generation plants, household and institutional solar PV system and related technical assistance and training
Price	N/A
Loan Details	30-years term with no interests, Credits do carry a small service charge of 0.75 % on disbursed balances.

Financing

Total Project Cost	**$105 M**	**100.0%**
International Development Association	$75 M	71.4%
Foreign Private Commercial Sources	$25 M	23.8%
Borrower (Republic of Uganda)	$5 M	4.8%

Source: the World Bank (http://web.worldbank.org)

Table 3. Case Study 2: Botswana - Morupule B Generation and Transmission Project

Case Study Overview

Organization	Botswana Power Corporation
Region	Botswana (2009 ~ 2014)
Purpose	Developing reliable supply of electricity and promoting alternative energy sources for low-carbon growth, Construction of a 600 MW (4 x 150 MW) coal-fired power station, Preparing a low-carbon growth strategy (50MW Solar targeted by 2016)
Price	5 cents/kWh (20 cents/kWh for Solar Power)
Loan Details	40-years term with no interests (IBRD), 20-years term with 1.336% interests (ADB), Financial IRR = 6.7%

Financing

Total Project Cost	**$905.4 M**	**100.0%**
IBRD – World Bank	$98.2 M	10.8%
African Development Bank (ADB)	$139.3 M	15.4%
Middle Income Country Trust Fund Grant	$0.6 M	0.1%
ICBC – Standard Bank	$535.7 M	59.2%
Borrower (The Government of Botswana)	$131.6 M	14.5%

Source: African Development Bank (http://www.afdb.org)

Table 4. Case Study 3: Argentina - Renewable Energies in the Rural Market (Permer)

Case Study Overview

Organization	Argentina Secretary of Energy
Region	Argentina (1999 ~ 2011)
Purpose	Providing electricity for lighting and radio & TV to about 70,000 rural households and 1,100 provincial public service institutions, installation of solar home system and decentralized energy supply, installation of Wind Home System (WHS) units in 2 small rural communities
Price	$8 ~ 10 per month, receiving 3 kWh monthly, (With Equipment Cost of about $3.56/month, $1.48/kWh per month)
Loan Details	15-years term with 0.87% interests ($30M from IBRD), 30-years term with no interests ($50M from IBRD)

Financing

Total Project Cost	**$170.5 M**	**100.0%**
IBRD – World Bank	$ 80.0 M	46.9%
GEF (Grant)	$ 10.0 M	5.9%
Government's Fund (FEDEI)	$ 26.5 M	15.5%
Concessionaires	$ 43.2 M	25.3%
Customers (Households or Institution)	$ 10.8 M	6.3%

Source: Source: the World Bank (http://web.worldbank.org) & Renewable Energy Information by Eric Martinot (http://www.martinot.info)

Table 5. Case Study 4: China - 1.9 MW Power Station at a Coking Plant

Case Study Overview

Organization	The Dongying Shengdong EMC (Commercial Company)
Region	China (2004)
Purpose	Building power stations that are capable of burning waste gases, provided by customers for free or at very low cost
Price	3.65 ~ 5.47 cents per kWh
Loan Details	1 year term, 90% of loan was guaranteed by GEF (Global Environment Facility) Funds with World Bank

Financing

Total Investment	**$900 K**	**100.0%**
Loan from Commercial Bank	$850 K	94.4%
Internal Funding	$50 K	5.6%

Source: ESMAP website (http://www.esmap.org) , Financing energy efficiency: lessons from Brazil, China, India, and beyond

2. First Revenue Satellite Economic Analysis

2.1. First Revenue Satellite (FRS) Financial Analysis Overview

An economic analysis for a First Revenue Satellite (FRS) for SSP applications will be examined here. The technical design is taken from other sources and does not originate from the authors. The SSP FRS examined for this analysis will be a 5 MW (delivered to ground) system for niche markets where there is limited access to electricity. An assumption is made that the system will operate for 10 years without need for refurbishment, similar to commercial telecommunications satellites.

The authors have updated their previous model called the Cost and Business Analysis Module (CABAM) to a new version, referred to as CABAM2.1. CABAM2.1 is a flexible financial analysis spreadsheet capable of modeling various space transportation and infrastructure projects. The model has a two-price input capability (Commercial & Government) with different market capture inputs for each market. Government contribution can also be analyzed. In this case it was evenly distributed during specific parts of the program and does not exactly match the expenditure of Design, Development, Test, and Evaluation (DDT&E) or acquisition cost. CABAM2.1 can also model equity / debt financing. The model can calculate output metrics such as Internal Rate of Return (ISS) and Net Present Value (NPV). For this analysis, the authors examined various government contribution scenarios. Three specific scenarios were examined including: no government contributions, 100% government contribution to DDT&E, 100% government contribution towards DDT&E and acquisition cost.

As a starting point, the authors used a specific concept design for a 5 MW SSP system. This specific system is the Naval Research Lab (NRL) Space Solar Power (SSP) 5 MW system (see Fig. 6). This system is not used as an optimum system for an SSP FRS application, but was available in the public literature and taken as a representative example of a notional, reference system. A specific description from the NRL of this concept includes the following[20]:

> The system uses a microwave transmitting antenna with a 1-km diameter. It assumes overall efficiency of 10% (intercepted sunlight to Earth electric power) using two solar arrays 152 m in diameter. The two arrays are fixed to the primary truss structure on the back of the transmit antenna facing the north-south axis. Flat solar reflectors in elliptical 165-m × 240-m rims rotate about this axis to track the Sun. Mantech SRS reflectors are of space-qualified polyimide with 94% reflectivity and an NRL-patented edge treatment that prevents distortions in the large areas of material. Both the antenna structure and the reflector rims are NRL large structures

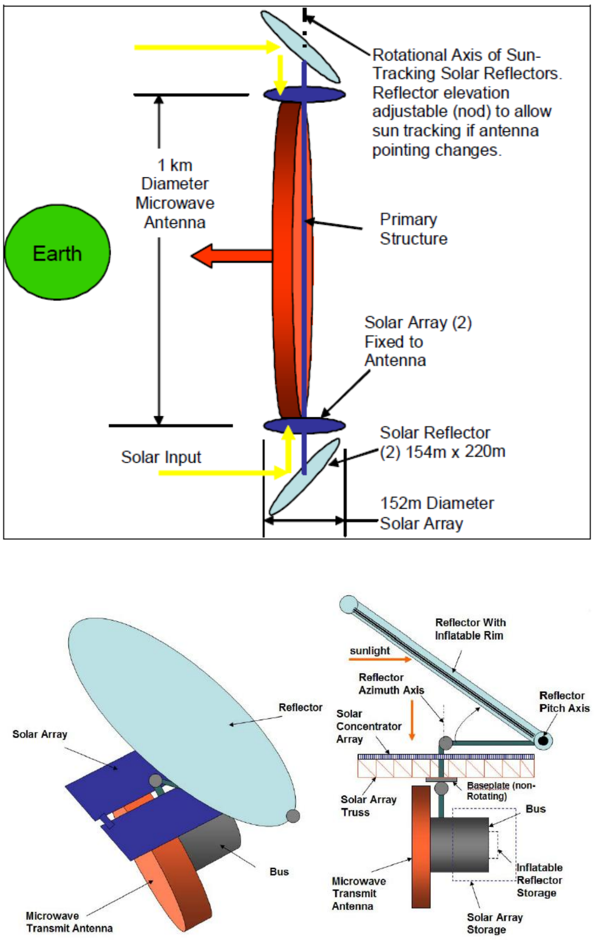

Fig. 6. Naval Research Lab (NRL) 5 MW SSP Concept[20]

2.2. CABAM2.1 Financial Model for SSP FRS

The authors developed a non-recurring cost estimate for the NRL 5 MW SSP FRS, using NAFCOM 2007 for the assessment. A mass statement (see in Table 6) was used as the starting point for a detailed cost estimate. The total mass of the spacecraft is 59.4 MT in Low Earth Orbit (LEO). No refurbishment mass was assumed for the system. The system is brought to LEO and then has a chemical propulsion stage to take it to GEO (final operational orbit). The Space Exploration Technologies (SpaceX) Falcon 9 launch vehicle is used in a six-launch architecture (assuming the satellite can be sub-divided into relatively equal mass elements). Cost for each Falcon 9 launch was assumed to be US$59.5M. A 100% duty cycle and 100% efficiency to the grid were assumed.

The cost assessment is deemed to be a conservative assessment using Weight-based direct Cost Estimating Relationship (CER) analogies for NASA historical satellites. Table 7 shows the outputs of the cost analysis, with an approximate cost of $4.8B for technology development, DDT&E, and acquisition. A system test hardware factor of 130% was input into NAFCOM (Fee: 10%, Program Support: 10%, Contingency: 20%). In-space dry mass equals 39,404 kg. DDT&E cost per kg (in-space dry mass) equals $78,396 / kg, acquisition cost per kg (in-space dry mass) equals $38,859 / kg, and DDTE + Acquisition Cost per kg (in-space dry mass) equals $117,255 / kg. These values for the space segment are in-line with typical government satellite projects on a $/kg basis. This is a preliminary cost estimate and the authors acknowledge it may need to be updated. Potential system modularity may reduce the specific cost ($/kg) down by an order of magnitude. The technical fidelity on the ground segment was minimal and thus very rough and perhaps overly optimistic estimates were made for ground system development and acquisition ($20M and $15M respectively).

Table 6. Naval Research Lab (NRL) 5 MW SSP Concept Mass Estimate[20]

Allocation	Total Mass (kg)	Comments/Basis
Attitude Control	50	Based on Upper Stage
Command & Data Handling	50	Based on Upper Stage
Communications	100	Based on Upper Stage
Mechanisms	500	
Energy Collection	20,000	250 W/Kg
Transmission Payload	10,000	TBD
Power Distribution & Wire Harness	704	Al Wire 1.4 kg/100m2 for 36000 m2
Thermal	300	3 large pump loop systems
Misc. Mass/ Margin	100	Estimate
Total Minus Propulsion and Structure	31804	Total of Non-Scaleable Subsystems
Propellant	20,000	LEO to GEO Transfer Plus 10 Yrs NS-EW GEO Station Keeping, 6000 m/s
Propulsion	2,200	Propulsion Dry Mass
Structure	5,400	Assume 10% structure
Total Space Vehicle	59404	

Table 7. Non-Recurring Cost of NRL 5 MW SSP Concept

Item	DDT&E Cost (in $M, FY2010)	Acquisition Cost (in $M, FY2010)
Technology Development (to TRL 6)	**$0.0**	**$0.0**
Phase A/B	**$60.1**	**$18.4**
TOTAL MAIN HARDWARE	**$2002.8**	**$612.3**
Spacecraft Bus	$982.6	$285.4
Transmission	$518.9	$192.9
Systems Integration	$501.3	$134.0
TOTAL WRAPS	**$936.2**	**$288.5**
Fee	$207.2	$63.8
Program Support	$228.0	$70.2
Contingency	$501.6	$154.5
GROUND SYSTEM	**$20.0**	**$15.0**
TOTAL	**$3,109.1**	**$1,546.2**

For this analysis, the SSP FRS program starts in 2015, with an initial operating capability (IOC) in 2020. Fig. 7 shows the notional timeline of development and operations of the system. The system consists of one satellite in GEO. Facilities cost were not included. Ground power storage and other facility costs are assumed to be provided by the market user. US$5M and US$1.45M (ground receiver refurbishment cost of US$100K, ground receiver system labor cost of 5 x US$150K, and ground operations labor cost of 3 x US$200K) were assumed respectively for space and ground segment recurring operations.

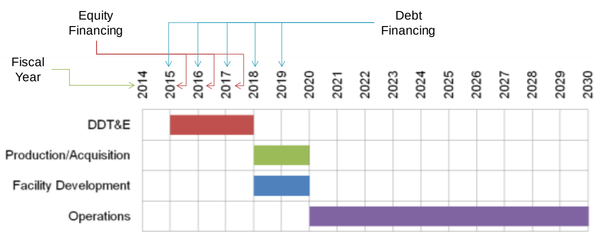

Fig. 7. SSP FRS Schedule.

Debt financing is assumed to cover all deficits after equity financing. Debt is repaid by the end of program. Table 8 gives some additional values for some of the financial variables used in the simulation. A baseline discount rate of 15% was used in the simulation. The program assumes US$300M of equity investment from 2015-2017 (requiring a 20% return) with dividend returning to the cash flow. Any additional cash needed in any years is then financing with debt through corporate bonds with 10 year terms (nominal interest rate of 4%). Debt is repaid by the end of the program. No tax credits are assumed in the simulation.

Table 8. SSP FRS Financial Modeling Assumptions in CABAM2.1

SSP System Characteristics	
Power per Solar Power Satellite	5 MW
Efficiency to Grid	100.0%
Nominal Duty Cycle	100.0%
Total Power Operating	5 MW

Launch Mass	
Base mass of each SPS	59.4 MT
Refurbishment % per year	0.0%
Number of SPS per year	1
Total Number of SPS	1
Total Launch Mass	59.4 MT

Transportation Cost	
Earth-to-Orbit	$ 5,694 /kg
In-Space: LEO-to-GEO	$ 0.00 /kg

SpaceX Falcon 9 ETO Launch Vehicle
(6 launches @ 10.45 MT/launch to LEO, US$59.5M/launch)

Ground power storage and other facility costs are assumed to be provided by the market user.

Cost Structure : Year of Cost = 2014

Amounts per SPS		Recurring: Operating	Recurring: In-space Transport	Non-Recurring: DDT&E	Non-Recurring: Production Acquisition	Non-Recurring: Facilities	Non-Recurring: Disposal
Space Segment	$M	5.00	0.0	2,989.1	1,531.2	0.0	0.0
Ground Segment	$M	1.45	0.0	20.0	15.0	0.0	0.0

Ground receiver refurbishment cost : $100K
Ground receiver system labor: 5 x $150K
Ground operations labor: 3 x $200K

Sensitivity Analysis with
0~100% Government Contribution

The financial analysis for the NRL 5 MW system using conservative assumptions results in pessimistic financial prospects for the system as a pure commercial venture (if output price for a 15% discount rate is compared to conservative military energy prices for forward operating bases). Table 9 shows the output financial results for three scenarios: as a pure commercial case, a case where the government pays for DDT&E cost, and for the case where the government pays for DDT& and acquisition cost. The output financial metric used for comparison is the price that needs to be charged in order to achieve the input discount rate given project cost estimates.

As seen in the first scenario in Table 9, DDT&E and acquisition costs are so expensive that the selected 5 MW satellite cannot cover the expenses for reasonable prices. A large amount of government contribution is required for reasonable price in niche markets (specifically for conservative military markets at $1/kWhr). Only when the government hands over an entire system en masse (as in the third scenario) it may then be possible to be competitive with many other forms of energy (given the optimistic assumptions on ground system cost). More detail on the second scenario is given in Figs. 8 and 9. This scenario is deemed the one to focus on given the unlikely nature of the first or third scenario.

Table 9. Financial Results for SSP FRS (Various Scenarios)

Government Scenario	Contribution Amount ($M)	Equity Investment	Price
No Contribution	$0 M	$300M total for first three years	$ 23.18 / kWh
100% DDT&E	$3,072 M	$300M total acquisition	$ 7.18 / kWh
100% DDT&E 100% Acquisition	$4,651 M	No Equity Investment	$ 0.15 / kWh

First Revenue Satellite (FRS) CABAM2.1 Financial Modeling Outputs: Price ($/kWh) at Break-Even Point
- 15% discount rate, cost of equity = 20%

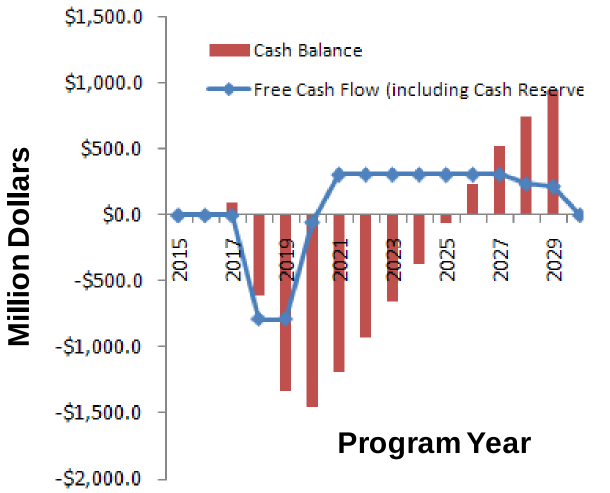

Fig. 8. SSP FRS: Firm Cash Balance for Govt. DDT&E Contribution Case (Government Contribution = 100% DDT&E, Equity Investment = $300M total during acquisition, Break-Even Price = $7.18 /kWh)

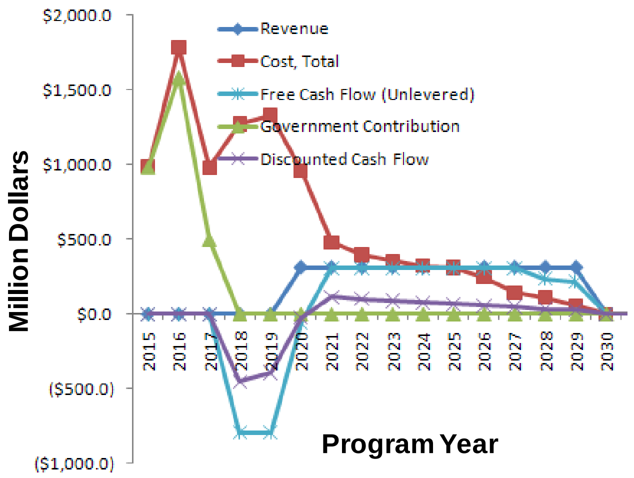

Fig. 9. SSP FRS: Firm Revenue and Cost Flows for Govt. DDT&E Contribution Case (Government Contribution = 100% DDT&E, Equity Investment = $300M total during acquisition, Break-Even Price = $7.18 /kWh)

An economic analysis of a conceptual First Revenue Satellite (FRS) based on a 59 MT (in LEO) SSP system delivering 5 MW to Earth yields about $7/kWhr in output price versus ~$1/kWhr for some potential sample niche markets. Future work that could improve this result would be a refinement of the system both in terms of technical optimization and cost analysis fidelity. One approach to the technical solution would be to constrain the LEO mass and then design the MW-class SSP FRS around that constraint. Thus for instance, the NRL 5 MW system used here has a mass in LEO of 59 MT. Space Exploration Technologies (SpaceX) has advertised their Falcon 9 Heavy vehicle with a capability of 53 MT to LEO. Thus that could be a design constraint or perhaps even a 70/100/130 MT in LEO design based upon the launch capability that NASA is looking into for its Heavy Lift Launch Vehicle (HLLV) as a follow-on to the Space Shuttle.

Additionally, if satellite cost per MWh and mass per MWh are known, a potential optimized power for the target price (e.g. $1/kWh) can be calculated. Future work on the FRS could include examining a more optimized technical design, looking at more specific customer scenarios (i.e. Nigerian universities, US military), utilizing different launch vehicle scenarios (one Falcon 9 Heavy versus six Falcon 9 launch vehicles), and examining the potential for additional financing schemes.

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