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Deploying Sunsats

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Abstract

This paper outlines an analysis of the cost of launching Solar Power Satellites, using launch technology available today. The economies of scale implied by any significant utilization of this energy source will reduce these costs to a level where they contribute less than 2.5¢/kWh to the cost of electric power produced by the system. The only major technical innovation that is needed is the introduction of reusable launch vehicles. While there is certainly room for improvements that would offer even lower costs, the conclusion is that the cost of spaceflight is not a serious impediment to realizing the advantages of power from space in the very near future.

Introduction

Projections by the U.S. Department of Energy and various international agencies indicate that in 2050 the world will require 2 to 3 times the 4500 GWe of electric generating capacity now available. Development and deployment of solar power satellites (sunsats) on a scale that makes a significant contribution to this need will be a major enterprise, but no technological breakthroughs are required. The only serious question is whether sunsats can be built at an acceptable cost.

A sunsat consists of a large solar array in geostationary orbit (GSO, 35,790 km above the equator). The power produced is transmitted by a microwave beam to a rectenna (rectifying antenna) near the intended load on Earth, and then converted to standard AC. The scale of construction demands mass production of components and systems, which means that equipment costs can be comparable to those for terrestrial applications. In particular, the much smaller collector area, the benign operating environment in free fall and vacuum (including the absence of weather), the delivery of power near the intended load and the avoidance of energy storage mean that the capital cost of the equipment for a sunsat can be considerably less than for a comparable terrestrial solar power plant. Of course, the price paid for these advantages is the need to deploy structures in space that are very large by current spaceflight standards. Whether or not sunsats can be competitive with terrestrial sources will therefore depend almost entirely on the feasibility of 1) a light structure and 2) a major reduction in the cost of launch to GSO.

It is important to recognize that spaceflight is not intrinsically expensive. The energy needed to place a payload in low Earth orbit (LEO) is ˜12 kWh/kilogram. If it were possible to buy this energy in the form of electricity at U.S. residential prices, the cost would be less than $1.30/kg. Rockets are very inefficient, but the cost of the propellants needed to reach orbit is typically less than $25 per kilogram of payload. The principal reason that launch to LEO is currently so expensive (>$10,000/kg) is that launches are infrequent - and they are infrequent because they are so expensive. Launch vehicles (LVs) are costly to build because the production volume is low; each LV is thrown away after one use. Annualized range costs are shared among just a few launches, and the staff needed for LV construction and launch operations are grossly underemployed. The quoted prices for launch would be much higher still were it not that in most cases the Department of Defense or NASA has absorbed the LV development cost.

The purpose of this paper is to demonstrate that the economies of scale in any significant space-based solar power (SBSP) program will permit launch at acceptable cost, even without major advances in launch technology. To be definite, a fairly modest sunsat deployment program is assumed, with the first launch taking place in 2015, leading to an installed sunsat capacity of 800 GWe in 2050. This goal will represent somewhere between 6% and 9% of the total global capacity that we will need by then.

The analysis uses simple standard models to approximate the performance and cost of LVs, with subsystem characteristics comparable to those of existing engines and vehicles. The only major technical innovation considered is the introduction of reusable LV stages, and the only major change in spaceflight practice is launch from an equatorial site. There is no attempt to optimize the launch architecture. Improved designs and advanced technologies will offer significantly lower costs than the rough estimates obtained here.

Sunsat Design

Sunsat modules are launched from an equatorial Pacific island to rendezvous with an assembly facility in equatorial low Earth orbit (ELEO) at an altitude of 200 n.m. (370 km). Transfer from there to GSO poses a problem, because a chemical rocket burning liquid oxygen and hydrogen (LOX/LH2) would require a mass ratio of 2.45 for the trip (this figure would be higher using any other common propellants). Delivering the necessary propellant from Earth would increase the mass to be launched, and thus the launch cost, by at least this factor. This may be acceptable when Earth launch costs become low enough (or when an extraterrestrial source of propellants becomes available), but it is prohibitively expensive when conventional LVs are used.

The sunsat assumed here solves this problem by using 25% of its solar array output for electric propulsion (by pulsed inductive thrusters[1] with a specific impulse of 6000 seconds) to drive itself up to GSO. The time in transit is 60 days and the required mass ratio is only 1.09. Slow transit of the Van Allen belts requires high radiation resistance, so solar dynamic conversion[2] is preferred to photovoltaics, at least for the solar array that is used for propulsion (the rest of the array might be packaged in radiation-proof containers for deployment in GSO). Since these systems require high solar concentration, the sunsat tracks the sun (during dayside passes) in both declination and right ascension. In order to minimize the attitude control authority needed to resist gravity-gradient torques while at low altitude, the sunsat is designed to be isoinertial while in transit mode (i.e., to have the same moments of inertia about all three principal axes). The configuration need not be strictly isoinertial once it is deployed in GSO, because the gravity-gradient torques are a factor of 250 smaller than in ELEO.

The frequency of the microwave power beam is in the ISM band centered at 5.8 GHz. The optimum power output from an Earth-located rectenna is then close to 2 GWe, comparable to a large nuclear power plant. Building a dual sunsat, feeding two independent rectennas via spot beams, facilitates inertial symmetry during orbital transfer. The result is a large structure: the collector area is 13.5 square kilometers.

Subsystem	Power Out GW	Mass MT
Two Rectennas	4.00	N/A
Two Microwave Antennas	5.52	6,900
Power Distribution	6.39	753
Solar Dynamic Modules	6.72	9,415
Pulsed Inductive Thrusters	0.74	811
	Sunsat structure	1,035
	Contingency, etc.	1,000
	Mass in GSO	19,914
	Orbital Transfer Propellants	1,822
	Mass in ELEO	21,736
	Specific Mass (kg/kW)	5.4

Table 1. Sunsat Systems

Table 1 gives a breakdown of the subsystem power outputs and masses. The specific mass (i.e., the mass that must be launched from Earth, divided by the power output to the terrestrial utility grid) is 5.4 kg/kWe.

Vehicle Models

The assumed buildup in installed SBSP capacity is shown in Figure 1 (black curve, left scale) with the corresponding mass to be launched each year (blue curve, right scale). The throughput to LEO is unprecedented, reaching more than 160,000 metric tons per year (MT/yr). Since the assembly facility in ELEO passes over the equatorial launch site every 98.1 minutes, there are 5,361 direct launch opportunities per year, which suggests an LV with a payload of about 30 MT. Note however that the initial launch is to a circular parking orbit at an altitude of 100 n.m. (185 km), which broadens the launch window by permitting compensation for brief delays in lift-off. This could also permit staggered launch of several LVs at each pass, providing an avenue for increasing the annual throughput if a more rapid buildup is needed.

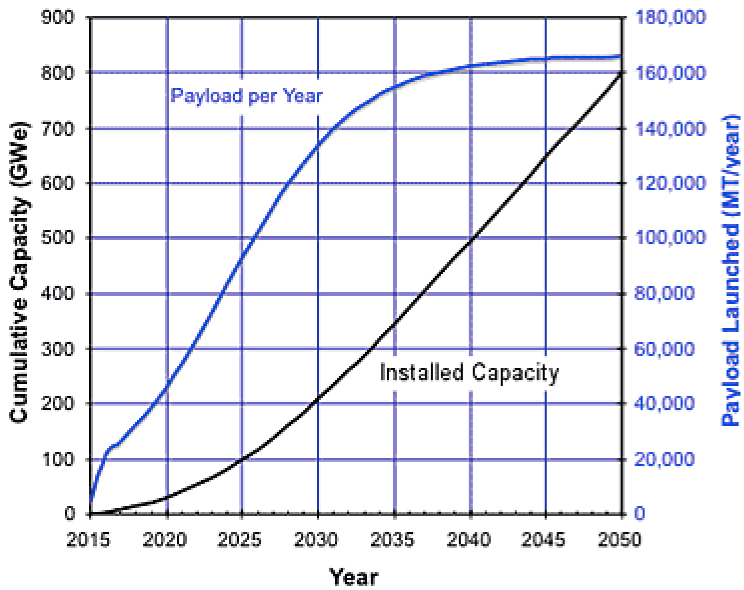

Fig. 1: SBSP Deployment Scenario.

The vehicles considered here are TSTO VTO LVs - i.e., two-stage-to-orbit rockets designed for vertical take-off. Both stages burn LOX/LH2 in engines similar to the Rocketdyne RS-68 and J-2S.[3] An orbital maneuvering system (OMS) burning storable propellants is used for transfer from the parking orbit to the facility and for de-orbit.

The nominal LV designs are based on a very simple launch model, in which drag and gravity losses are incorporated by assuming a ΔV for launch to the parking orbit of 9.2 km/s. The inert mass of each stage and the masses of the subsystems needed for recovery (reentry protection, wings and landing gear) are estimated using standard mass estimating relationships (MERs) that represent the present state of LV technology. Three variants are considered, all with a payload of approximately 30 MT: a) both stages are expendable; b) 1st stage is reusable, 2nd stage is expendable; and c) both stages are reusable. Recoverable stages are equipped with wings and landing gear: after staging, a reusable 1st stage glides to a runway on an island downrange, while a reusable 2nd stage docks with the

ELEO facility and remains attached until it is in position for reentry and return to a runway at the original launch site.

1st Stage	Expend	Reuse	Reuse	
GLOW	679.8	906.5	1586.3	MT
Inert Mass	73.4	130.5	228.4	MT
Engine	RS-68	RS-68	RS-68	
Number	3	4	7	
Staging At	4.45	4.86	5.07	km/s
Ground Crew	5	5	12	
2nd Stage	**Expend**	**Expend**	**Reuse**	
Initial Mass	133.3	119.3	185.9	MT
Inert Mass	14.4	12.9	33.5	MT
Engine	J-2S	J-2S	J-2S	
Number	1	1	1	
Payload	27.8	28.7	30.0	
Ground Crew	4	4	8	

Table 2. LV Characteristics

The calculated characteristics of these LVs are shown in Table 2. In each case, the staging velocity was chosen to minimize the average launch cost (see below). Also shown are the number of groundcrew assigned to each stage. Note that, because of the extra equipment needed for reusability, the gross lift-off weight (GLOW) of the fully reusable vehicle is more than twice that of the ELV, and its first stage requires 7 RS-68 engines, versus 3 in the latter.

Launch Cost

Approximate values for the first-unit costs for engines and complete LVs were calculated using the cost-estimating relationships (CERs) in NASA's heuristic Spacecraft/Vehicle Level Costing Model (SVLCM).[4] The CERs, while not very accurate, are a distillation of the agency's experience to date with expenses incurred in cost-plus-fixed-fee government contracts, so they generally offer conservative estimates of cost reductions that may be achieved in a competitive commercial environment. The cost of subsequent production runs follows a 90% learning curve – i.e., the unit cost of a given system decreases by 10% every time the number produced doubles.

The LV fleet size and production rate needed for the launch campaign were calculated using an average life of 80 flights and a turnaround time of 7 days for reusable 1st stages and 50 flights and 4 days for reusable 2nd stages. Range costs were estimated as a flat $200 million/year, regardless of launch activity. Annual loaded labor costs were taken as $225,000 per person. The direct operating costs for launch using these LVs are shown in Figure 2 as functions of time during the SBSP buildup. Despite the much larger vehicle for a similar payload, the RLV offers costs that are an order of magnitude lower than for the ELV.

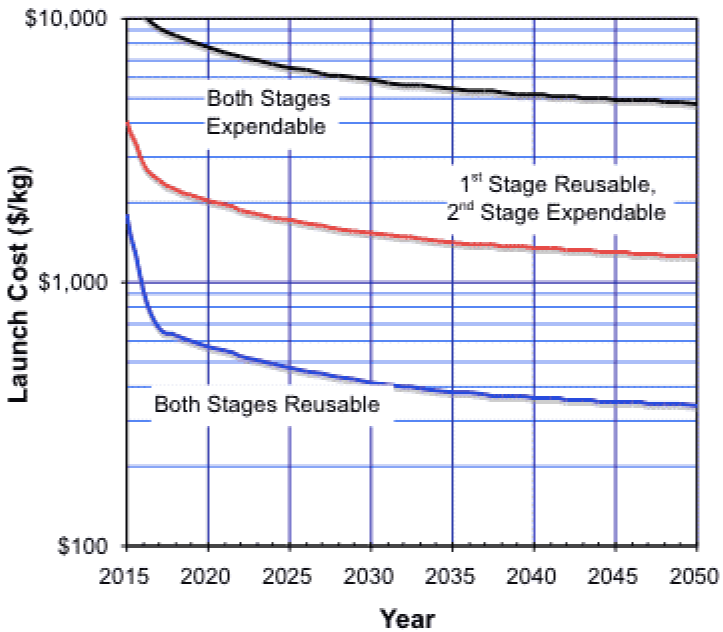

Fig. 2: Launch Cost History.

In order to assess the commercial feasibility of deploying sunsats at these launch costs, it is assumed that launch services using the fully reusable LV are priced at a constant figure from the outset of the buildup. Figure 3 shows the cumulative cashflow to the launch contractor for several values of this constant price. The minimum figure is $403/kg, which would not reach breakeven until the end of the deployment scenario in 2050.

The contribution of launch costs to the capital cost of the sunsat is obtained by multiplying the launch price by the specific mass, given in Table 1 as 5.4 kg/kWe. For example, a launch price of $450/kg would add $2,430/kWe to the overnight cost of the system. If this cost is amortized over a sunsat life of 25 years at a discount rate of 6%, and if the system operates 95% of the time (i.e., for 8,328 hours per year), the launch would contribute 2.28¢/kWh to the cost of the electricity produced. The costs/kWh due to the other launch prices are shown in the legend of the figure, assuming the same amortization schedule.

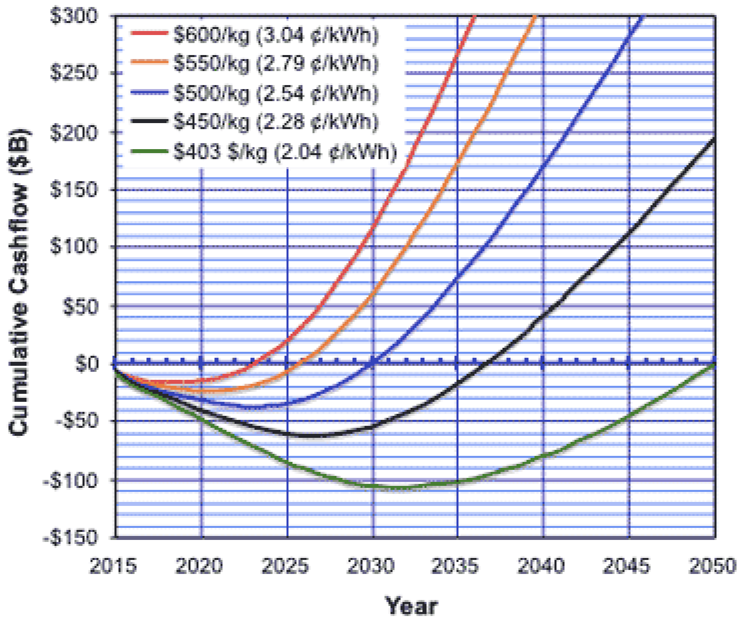

Fig. 3: Launch Operations Cumulative Cashflow.

The costs shown here include construction of the LVs but not their development. The reason is that the heavy traffic to orbit needed for SBSP would make much lower launch costs available to all users of space. In particular, levelized launch pricing in the context of this SBSP deployment scenario would offer the DoD and NASA an immediate reduction by a factor of 20 in their expenditures for space launch. Given a commercial or government commitment to a significant SBSP program, a strong case can thus be made that funding commercial development of a fully reusable heavy-lift vehicle that meets their needs as well as those of SBSP is well within the mission and serves the direct interests of these agencies.

Conclusions

It is clear from Figure 3 that the principal problems in closing the business case for a launch services provider that supports SBSP are related to financing the venture rather than to the cost of operations or the eventual profitability. For example, a launch price of $450/kg leads to a maximum deficit of $60 billion in the 12th year of the deployment schedule, and the cumulative cashflow does not become positive until the 22nd year – but the end result in 2050 is a profit of $180 billion. The delay in profitability exceeds the planning horizon of most venture capitalists, so the project probably requires both a strong government commitment to completing the deployment as well as some form of financial guarantee. Creative financing could help: for example, the launch price could be set at $600/kg in the early years, with a contractual obligation to refund some of the money once the cashflow went positive.

The particular systems assumed in this analysis (LOX/LH2 in both stages, winged recovery, etc.) should not be taken as recommendations for design of RLVs for this application. The purpose is only to show by example that the cost of launch to LEO is not a reason to delay implementation of SBSP as a major contributor to energy supply in the United States and around the world. The need is urgent and the best time to begin a serious development program is right now.

REFERENCES

1. These high-power thrusters have been under development by NASA for decades. See Frisbee, R.H., & Mikellides, I.G., "The Nuclear-Electric Pulsed Inductive Thruster," 41st AIAA/ASME/SAE/ ASEE Joint Propulsion Conference, 2005. This paper is available at http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/38357/1/05-1846.pdf.
2. Solar-powered closed Brayton-cycle turbogenerators for use in space have also been under development by NASA for decades. See L. Mason, "A Solar Dynamic Power Option for Space Solar Power," 34th Intersociety Energy Conversion Engineering Conference, Vancouver, August, 1999. Available at http://gltrs.grc.nasa.gov/reports/1999/TM-1999-209380.pdf.
3. The J-2S is a simplified version of the engine that powered the upper stages of the Saturn 1B and Saturn V for the Apollo program. The RS-68 powers the Common Booster Core of the Delta IV evolved expendable launch vehicle (EELV). Some modifications to these engines would be needed to enable multiple reuses with little refurbishment between flights, but much of the development is a sunk cost. A bigger engine would be preferable for the 1st stage, and a hydrocarbon fuel might reduce cost. A good example is the RS-84, a LOX/RP-1 engine that offered 50% more thrust than the RS-68 and was designed for at least 100 restarts, but NASA terminated its development in 2004 because it was not needed for Project Constellation.
4. NASA Cost Estimating Web Site. Spacecraft/Vehicle Level Cost Model, at http://cost.jsc.nasa.gov/SVLCM.html.