A Solar Power Satellite Sending an Infrared Beam from GEO to 40% Efficient Concentrating Solar Power Modules on the Ground 24 Hours per Day

Lewis M Fraas[1] & Mark O'Neill[2]

[1] *JX Crystals Inc, Issaquah, WA 9802*
[2] *Mark O'Neill LLC, Keller, TX 76248*

Harvesting solar energy in space from a GEO orbit and RF beaming it down to earth has been a dream since the oil crisis in the 1970's. However, the colossal and expensive first step required to achieve this goal has stifled its initiation. The problem derives from the dispersion of the beam associated with the long RF wavelength leading to a multi km size receiver station and a km size satellite and a costly multibillion dollar development project for a GW sized satellite. Using a shorter wavelength infra red beam reduces the dispersion and ground station size and consequently the satellite size from GWs to MWs or less. Herein, a satellite with a diode pumped Er:YAG laser generating an IR beam is proposed. The 40 m diameter ground station can receive eye safe IR radiation. Modular concentrating IR arrays with GaSb IR photovoltaic cells can then generate electricity 24 hours per day with an efficiency of 40%. The economics for this concept are described and promising for national security niche power markets.

Nomenclature

CPV = Concentrating Photovoltaics
Er = Erbium
GaSb = Gallium Antimonide
GEO = Geosynchronous Orbit
GW = Giga Watt
IR = Infrared
kW = Kilo Watt
kWh = kW hour
MW = Mega Watt
RF = Radio Frequency
SPS = Solar Power Satellite

I. Background – GW SPS in GEO with Microwave Power Beam

The idea of harvesting energy in space and then transporting it to the ground was suggested at the dawn of the space age [1]. Initial proposals made use of converting sun-generated electricity into microwaves, which would then be power-beamed to the ground. Fig.1 shows one SPS concept, the 5 km by 15 km "Integrated Symmetrical Concentrator" [2]. Solar energy is collected by the two large mirror arrays, converted to a microwave beam and transmitted to an 8 km diameter Rectenna field and then converted into electric power.

As Jaffe et al [3] point out in table I, the problem for microwave beaming Solar Power Satellites derives from the dispersion of the beam associated with the long microwave wavelength leading to a multi km size receiver station and a km size satellite and a costly multi billion dollar development project for a GW sized satellite. Using a shorter 1.5 micron wavelength infra red beam reduces the dispersion and ground station size and consequently the satellite size from GWs to MWs.

Table I: Comparison of Microwave and Laser Power Transmission for SPS from GEO [3].

	Microwave	Laser
Transmit frequency (Wavelength)	5.8 GHz	1.5 microns
Transmit Aperture Diameter in GEO	1 km	2.5 m
Receiving Aperture Diameter on Ground	3.2 km	40 m

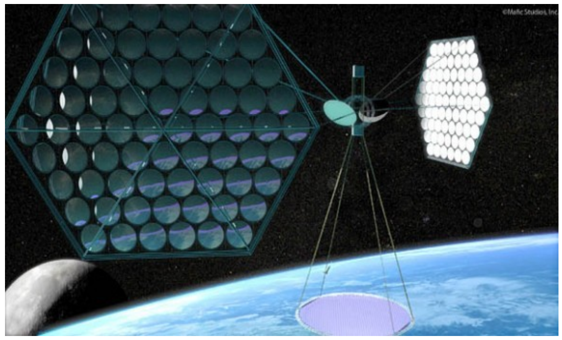

Figure 1: Artist concept for the Integrated Symmetrical Concentrator Solar Power Satellite [2].

II. Background – MW SPS in LEO with IR Power Beam

The main problems with using a microwave-based system were the huge size of the required receiver on Earth, and the stringent performance requirements of the focusing system. Later on in the seventies, scientists at the Lawrence Livermore National Laboratory (LLNL) suggested using laser light instead of microwaves, thereby reducing the requisite focal spot size; which in turn reduced by a thousand fold the overall size requirements for the receiver and focusing optics.

In 2009, A.M. Rubenchik et al [4] from Laurence Livermore National Lab proposed the SPS system shown in figure 2. A key element of this suggested system is highly efficient, electrical diode pumped laser presently being developed at LLNL [5]. The laser efficiency from electricity to light is approximately 50% with a 5kg/KW weight-to-power ratio and very good beam quality, which is a key requirement for propagating the laser beam from space to the collection receivers on Earth.

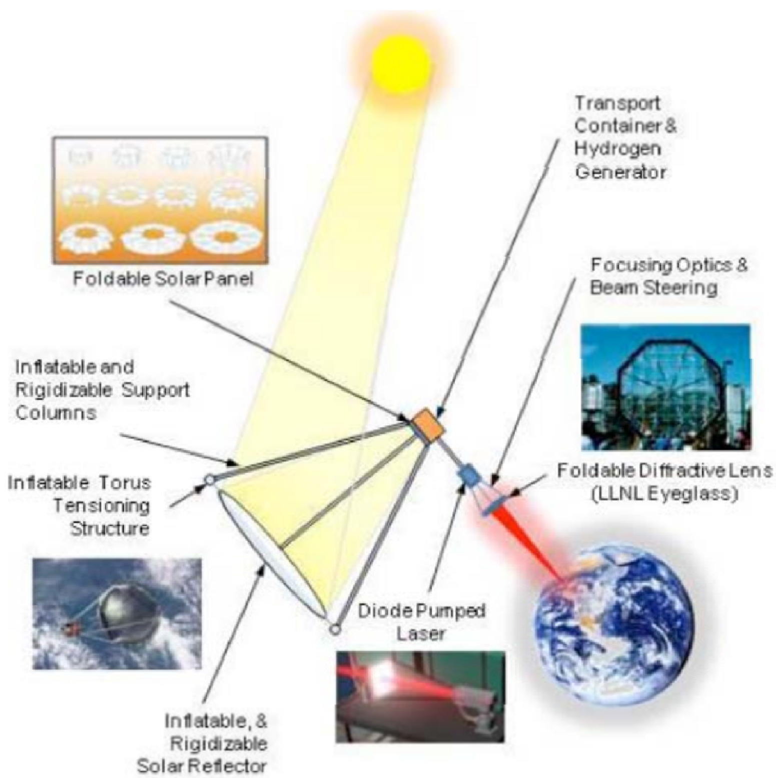

Figure 2: Overview of the IR Solar Power Beaming System in LEO [4].

III. Concept – MW SPS in GEO with IR Power Beam

There are some potential improvements possible for the figure 2 concept. First, the large inflatable solar reflector can be replaced by a distributed modular concentrator photovoltaic (CPV) array. Second, the diode pumped fiber laser can be an Er:YAG laser emitting eye-safe IR at 1.5 microns. Third, the SPS package can be sent to a GEO orbit, not LEO. And fourth, the ground station can be 40 m in diameter equipped with IR GaSb cells in CPV electric power generating arrays. The following sections outline these and other potential improvements.

A. Distributed PV Array

For the solar panel in the figures 1 and 2 concepts, the multijunction 40% efficient InGaP/GaInAs/Ge concentrator cell originally described by Fraas et al [6] and subsequently demonstrated by King et al [7] are to be used. However these concepts concentrate all of the solar energy to a central cell receiver which then creates a waste heat management problem as well as non-uniform irradiance on the many solar cells interconnected in the receiver. A distributed solar concentrator array is preferred using an array of lenses with each lens focusing sunlight onto an individual cell. Waste heat is efficiently spread over an ultralight radiator which rejects this waste heat to space, keeping the cells cool. The lightest and most cost-effective approach uses the robust, ultra-light Fresnel lens solar concentrator modules recently developed by a team organized under funding by NASA [8-10]. The basic building block of the 25X point-focus Fresnel lens space photovoltaic concentrator is shown in Fig. 3. The 25X concentration was selected to accommodate $\pm 2^{o}$ of sun-pointing error in any direction.

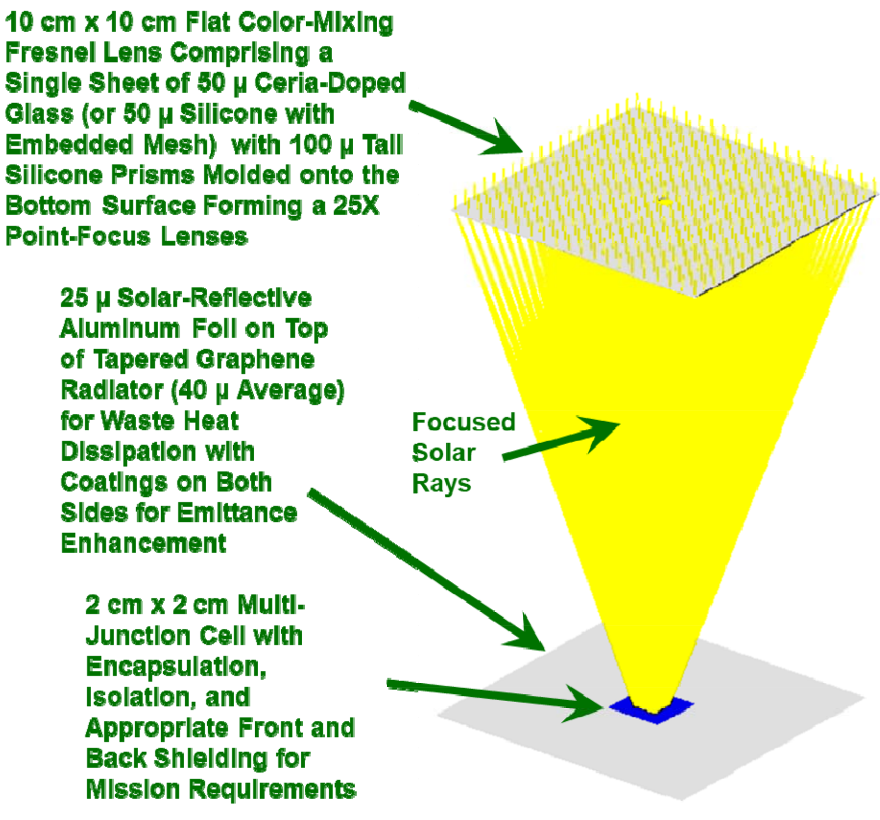

Figure 3: 25X Space PV Concentrator Schematic [8].

Orbital ATK (now Northrop Grumman) performed a detailed parametric design and analysis program for NASA to quantify the advantages of the 25X point-focus concentrator on their Compact Telescoping Array (CTA) deployment and support platform for various array sizes from about 20 kW to about 350 kW for Extreme Environment Solar Power (EESP) missions [10]. Their basic space solar concentrator array design is shown in Fig. 4. Their key results are shown in Fig. 5. Note that they concluded that the cost of the 25X concentrator array would be more than 60% lower than for a conventional one-sun array, and the mass would be more than 50% lower than for a conventional array.

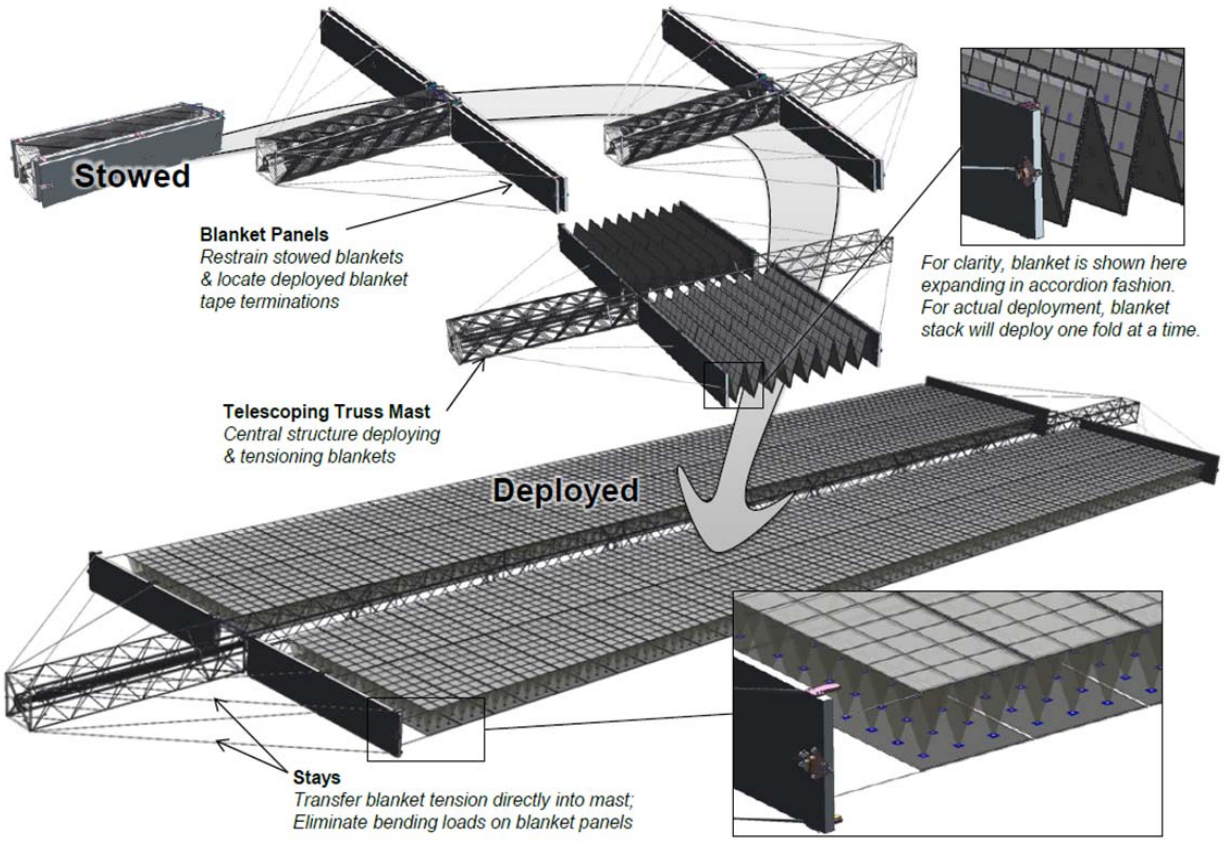

Fig. 4: 25X Point-Focus Concentrators on Compact Telescoping Array Platform for NASA's Extreme Environment Solar Power (EESP) Deep Space Missions [10].

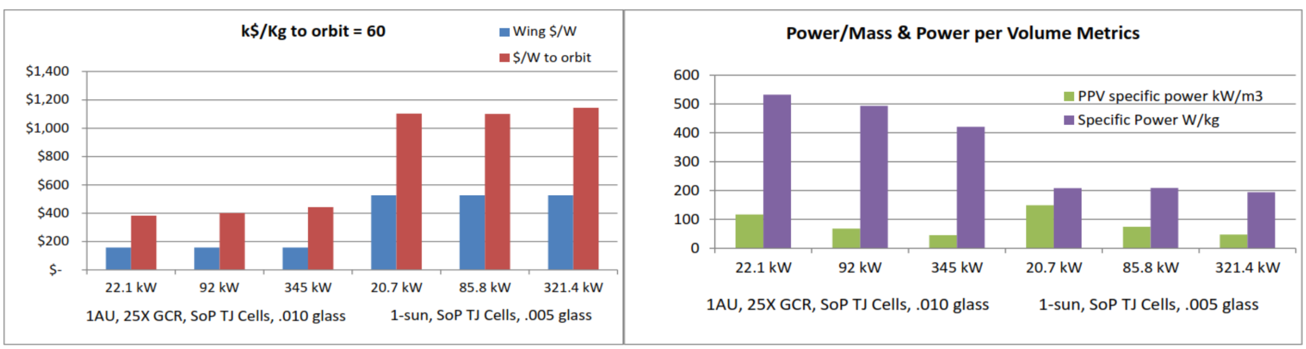

Fig. 5. Cost and Performance Metrics of Point-Focus Concentrators on Compact Telescoping Array [10].

B. Eye safe diode pumped Er:YAG laser at 1.5 micron

nLight [11] makes the diode laser pumped Er:YAG lasers shown in figure 6. The 1.5 micron wavelength emitted is eye-safe.

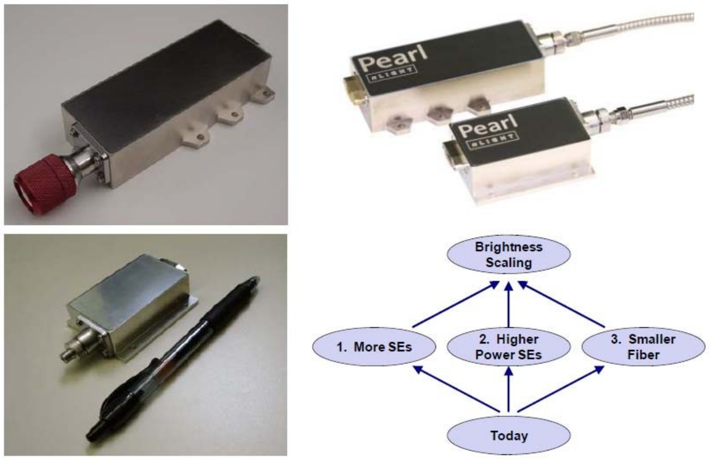

Figure 6: (Top left) Photograph of a conductively-cooled nLIGHT Pearl™ package with optional external lens for collimated output. This unit achieves a divergence of < 6 mrad (fast and slow axes) with beam diameter of < 9x12 mm (Top right) Two fiber-coupled nLIGHT Pearl™ modules. (Bottom left) Photograph of a Pearl™ module next to a common ink pen to emphasize its relative size. The unit weights ~500 grams. (Bottom right) Module brightness can be scaled in three independent ways. Coupling to smaller fiber is achieved through improvements in optical alignment and diode emitter brightness [11].

C. Ground site with 1-sun equivalent IR power density

The laser beam intensity at the ground site for the LEO SPS Figure 2 concept is 10 W per sq cm, hot enough to fry birds. It will be preferable to locate the figure 2 or 4 SPS at GEO with about a 1 MW beam incident on a 40 m diameter ground receiver site. The beam intensity would then be 1 MW/20x20x3.14 sq m = 1000 kW/1256 sq m = 800 W / sq m or approximately 1 sun equivalent.

D. CPV receiver station modules on the ground using GaSb IR PV cells

The ground receiver can consist of Concentrating solar modules and arrays similar to those made by Soitech as shown in figures 7a and 7b. These Soitech arrays [12] used 40% efficient multijunction solar cells.

(a) (b)

Figure 7 a & b: Fresnel lens high concentration PV (HCPV) module and arrays using 40% efficient solar cells as developed by Fraunhofer and Soitech.[12].

However, the modules and arrays shown in figure 7 could just as well be equipped with GaSb photovoltaic cells. GaSb cells have been used in the concentrator array shown in figure 8 and GaSb receiver circuits similar to the one shown in figure 9 have been used as IR power beaming receivers [12]. Their calculated efficiency with 1.5 micron IR radiation should be 45%.

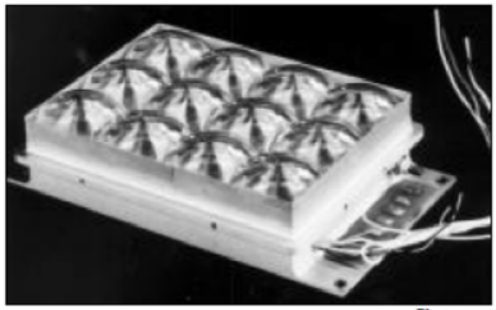

Photo courtesy of NASA

Figure 8: Photo of the CPV array using GaSb IR cells in the PASP+ Mini Dome Concentrator experiment [12].

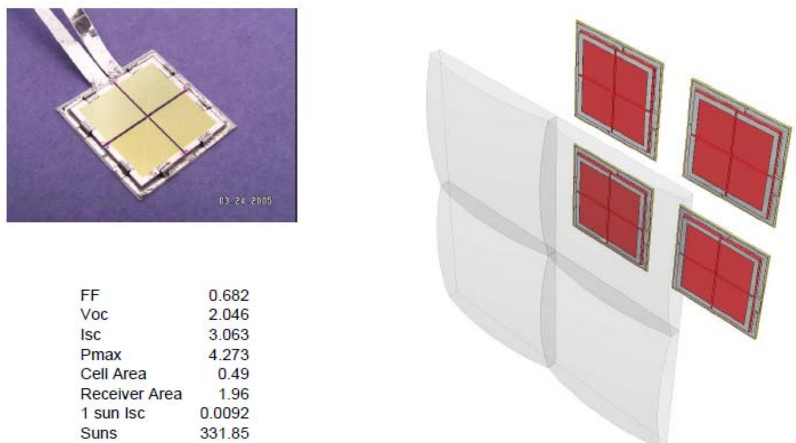

Figure 9: GaSb Circuit [12] for 1.5 micron IR power Beaming. Example 16 W at 6 V. Efficiency with 1.5 micron or 0.8 eV IR = 0.5 Vx0.7/0.8 = 0.35/0.8 = 44%; With 90% QE = 40%

Note that in the GEO SPS system proposed here, the modules are simply pointed at the fixed local celestial location in the sky where the GEO SPS is located just as for a direct broadcast TV satellite dish. The satellite location in the celestial sphere does not move at all year around. No tracking is required for the ground concentrators.

E. Rough Order of Magnitude Sizing

When discussing cost, the discussion will be in terms of dollars per AC Watt. To deliver 400 AC kW to the grid, we will need about 2.7 MW of power output from the space photovoltaic concentrator system. The conversion losses are enumerated in Figure 10. The efficiency from space array solar electric power to ground AC power is 14.8%

CPV GEO array	2.7 MW
50% Laser efficiency	1.35 MW
DC power with 45% 300 C cell efficiency	608 kW DC
DC power at operating cell temperature	555 kW DC
Atmosphere & Lens transmission efficiency 80%	444 kW DC
DC to AC inverter efficiency 90%	400 kW AC

Figure 10: Space array solar electric power to ground electric AC Watts.

F. SPS in GEO Specification and Launch to GEO

One of the key issues for SPS has been the problem of launch cost to GEO. In early SPS studies, NASA assumed an eventual launch cost of $200 per kg and noted that eventually, reusable launch vehicles would be needed. Now SpaceX [13] has demonstrated reusable launch vehicles but launch costs are still well over $200 per kg.

The Falcon 9 pay load to GEO is: 8,300 kg. Table II gives an estimate for the modified figure 2 and figure 4 SPS target weights. The figure 2 SPS weights come from Rubenchik (4). The CPV array weights for the figure 4 SPS come from figure 5. As discussed above, we will need about 2.7 MW of space photovoltaic concentrator output to provide about 400 kW of net electricity to the grid on the ground. Given the estimated specific power of 400 W per kg from figure 5, then a 2.7 MW CPV array should weigh approximately 2.7x10^6/0.4x10^3 = 7,000 kg.

Table II: Target component weights for GEO 1 MW SPS.

System	Fig 2 SPS	Fig 4 SPS
Subsystem Weight	Weight (kg)	Weight (kg)
Solar Reflector	3000	7000
Solar Collector	300	
Packaging Container w/ utilities	450	450
Diode Pumped Laser System	4100	4100
Focusing and Beam Director System	400	400
Total Weight	8250	11950
Total Packaged Volume	2 m square by 4 m tall	

IV. Cost and First Market

Figure 11 shows the estimated cost of GaSb cells as a function of volume production [12]. Given an approximate 400 kW output from the ground system, one would anticipate a GaSb cell cost of under $3 per W. Adding the cost of the lens, housing, and pointing structure, the 400 kW ground site should cost less than $10 per W or $4 million.

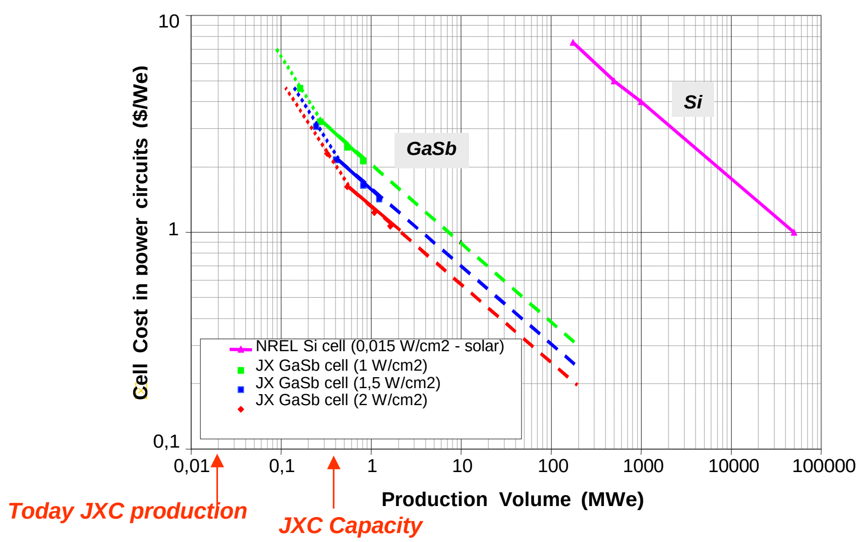

Figure 11: Estimated cost of GaSb cells as a function of volume of production.

Recently, the National Security Space Office (NSSO) published a report emphasizing the demand for local energy supply in the megawatt range for remote bases and villages, etc [14]. J. Mankins [15] also described a national security premium niche power market at a price of \$3 per kWh. At this market price, one can calculate the annual revenue for a 400 kW facility as \$3 x 400 x 24 x 365 = \$10.5 million.

One can also calculate an allowed system cost with solar PV as a starting point. Assume as a starting point from terrestrial solar that \$2/W equates to 10 cents per kWh for 8h per day of 1kW/m^2 of sunlight. Then with 1 kW/m^2 of IR for 24 h per day, 10 cents per kWh would equate to \$6/W. Now assume a national security premium niche power market with an allowed \$3 per kWh, then the allowed system cost would be 30x\$6/W or \$180 per W. Now assume 400 kW of ground electric power, then the allowed system cost would be 400,000W x \$180/W = \$72 million. From the above annual revenue, one can note that if the system were to cost \$72 million, the payback time would be about 7 years.

Now assume that the cost to deliver a payload to GEO is \$1,500 per kg, then the cost to deliver a 10,000 kg payload to GEO would be \$15 million. Now assume that the 400 kW ground CPV station can be made for \$10 per W, then it would cost \$4 million. This will leave a budget of \$72 million - \$19 million = \$53 million to deliver the Space Power Satellite to the launch pad. This is \$53 million / 2.7 MW=\$20 per GEO CPV solar W. This is a plausible scenario if not for the first SPS given the additional development requirement, it is still quite plausible for subsequent SPS systems.

Finally, now let us address the initial SPS development. The fact that both the GEO figure 4 and ground figure 7 CPV arrays are modular has an additional advantage in that the initial development can be begun at levels well below one MW. Specifically, note that the figure 7 CPV module is designed to operate with an illumination intensity of 1 kW per square m. However, it could be initially tested at an illumination level of 20 W per square m. This means that the IR laser in GEO could be a 20 kW laser and the initial GEO demonstration SPS array could be a 40 kW array.

Now referring back to figure 5, note that the cost data are presented in two forms: (1) the delivered array cost prior to launch (blue bars), and (2) the array cost placed in orbit including launch costs (red bars). Both costs are for a single array for a single mission. If we focus on just the delivered array cost for the 25X concentrator, it is about \$150 per Watt for any of the array sizes (20 kW, 90 kW, or 320 kW). If we consider the space solar power application discussed in more detail in the previous sections, we will need a space solar array of about 2.7 MW to power the laser power beaming system in space to ultimately deliver 400 kW of grid electricity on the ground. If we consider mass production of the 20 kW building block from Fig. 5, with a hardware price of about \$150 per Watt, the 2.7 MW space solar power system will be much cheaper per Watt due to normal learning curve cost reductions. USAF Lieutenant Colonel Peter Garretson describes the need to use such learning curves in estimating the price of space solar power systems [16]. Using this approach, Fig. 12 shows the falling price per Watt for this space solar power application from the first 20 kW to a cumulative production of 2,700 kW for three different assumed values of the learning curve reduction factor. We believe that the most realistic factor is about 70% based on the solar market learning curve in figure 11 and [17]. The values on the curves are the costs of the last 20 kW produced. For the first space solar power system, the average price from the first to the last 20 kW produced for a cumulative production of 2,700 kW is the best estimate for this first system. Note that the average cost for the 70% learning curve is about \$23 per Watt. We think this is a very reasonable goal.

Fig. 12. Space Solar Array Cost Estimate Based on Learning Curves

V. Conclusion

A plausible design for a first viable space Solar Power Satellite has been presented. Herein, a satellite with a diode pumped Er:YAG laser generating about a 1 MW beam is proposed. The 40 m diameter ground station receives eye safe IR radiation with a 1-sun intensity of approximately 1 kW per square m. It uses 40% efficient modular concentrating photovoltaic arrays with GaSb IR photovoltaic cells to generate 400 kW 24 hours per day to clear sky locations. The economics for this concept are presented and promising for national security niche power markets.

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