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Sunbeams from Space Mirrors Feeding Solar Farms on the Ground at Dusk and Dawn

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Sunbeams from Space Mirrors Feeding Solar Farms on the Ground at Dusk and Dawn

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ABSTRACT

For 40 years, the systems designers of space solar power have given their greatest attention to wireless power as microwave transmission from space to earth. The approach taken in this application is to place space satellites in lower sunsyncronous orbits for the purpose of gathering and focusing sun's rays into a beam of reflected sunlight. The simple idea and application of this design is to extend the solar day of terrestrial solar farms, thereby increasing solar production capacity to 60 percent and reducing solar electricity costs to under 6 cents/kWh by delivering sunlight to a given location some 14 (rather than 6 or 7) hours per day.

Reflected Sunlight from Space Journal on Vimeo.

TECHNICAL BRIEF

Sunbeams from Space Mirrors Feeding Solar Farms on the Ground at Dusk and Dawn.

Lewis Fraas, President, JX Crystals

Note to reader: The body of research on which this briefing is based may be found in References below.

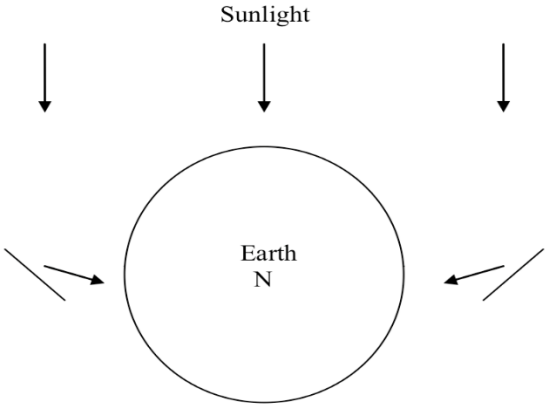
Large Terrestrial Solar Fields are being installed but electric power production in evenings & winter is desirable:

Photographs of multi MW solar PV power fields in India, California and Germany.

Concentrated Solar Power Fields are also potential Targets for more solar electricity in the early morning and Evening for lower cost electricity

Photographs of 100 MW CSP field in Abu Dhabi In 2013

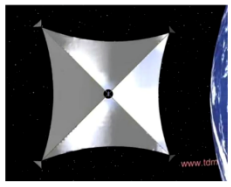
Innovation



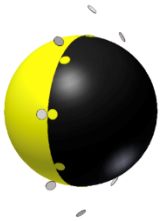
Revolutionary Concept:

Lightweight mirrors in a Dawn-Dusk Orbit beam sunlight to earth PV stations providing solar electricity in evening & winter for 14 hours per day increasing solar power station capacity factor to 60% & reducing Solar electricity cost to Under 6 cents / kWh.

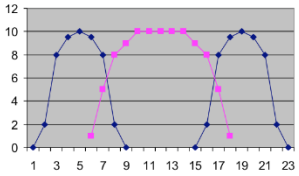
NASA L' Garde Sunjammer



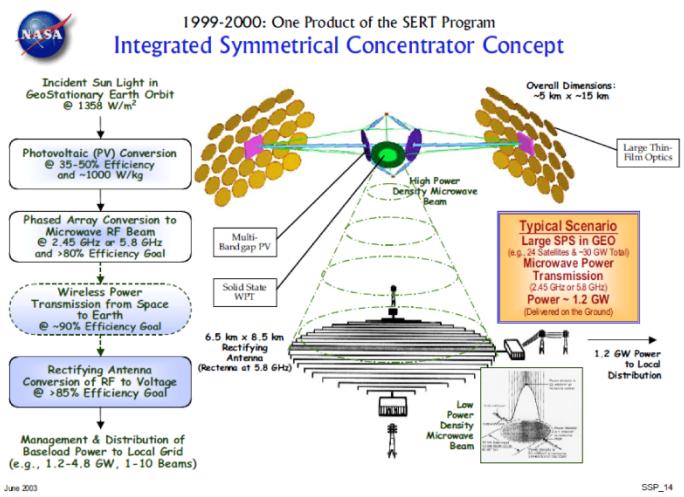
Space Mirror



Space Mirrors Normal Sunlight

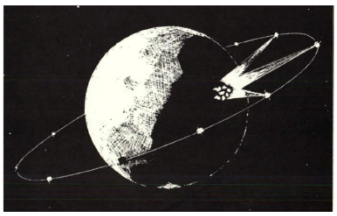


Space Power Beaming Prior Art Concept – Very Complex



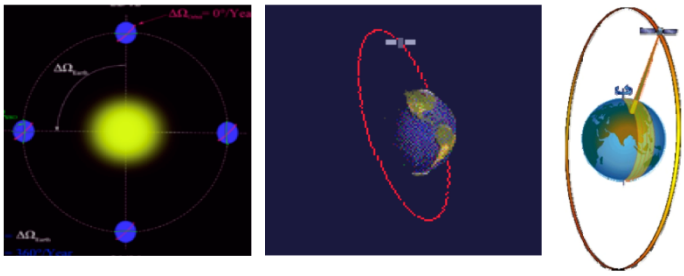
Power Soletta Proposal

Dr. Ehricke's 1978 Prior Art Concept



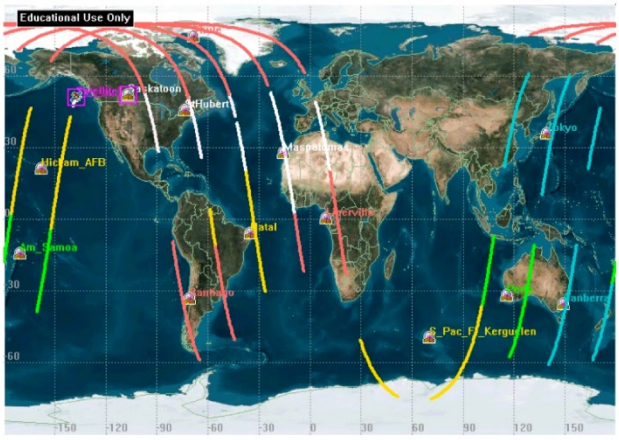
Advantage:	Problems:
Mirrors in space beaming sunlight to earth is simpler than converting it to electricity and then microwave beaming it down and converting it back again to electricity.	**1.) 4200 km orbit** **2.) Sun's disc size is 10 mrad** **42 km diameter spot on earth** **3.) 180 GW power station**

Present Proposal: Put Mirrors in Dawn to Dusk
1000 km Sun Synchronous Low Earth Orbit

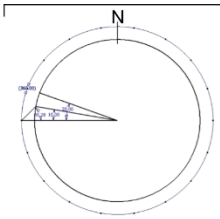
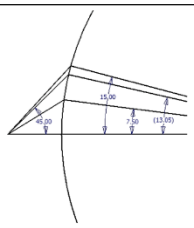
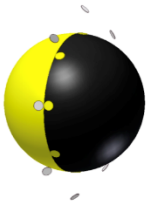


Advantages:
1.) Sweeps a 10 km wide sunbeam over each point on earth for 2 hours in early morning and 2 hours each evening.
2.) Multiple earth ground stations possible with 5 GW per station.

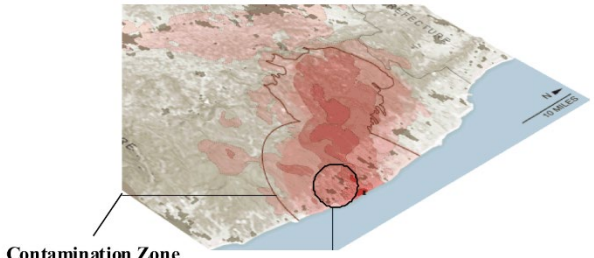
Track for a Dawn to Dusk Satellite
(Multiple Satellites will cover all +/-80 latitudes)



Proposed Mirror Satellite Constellation

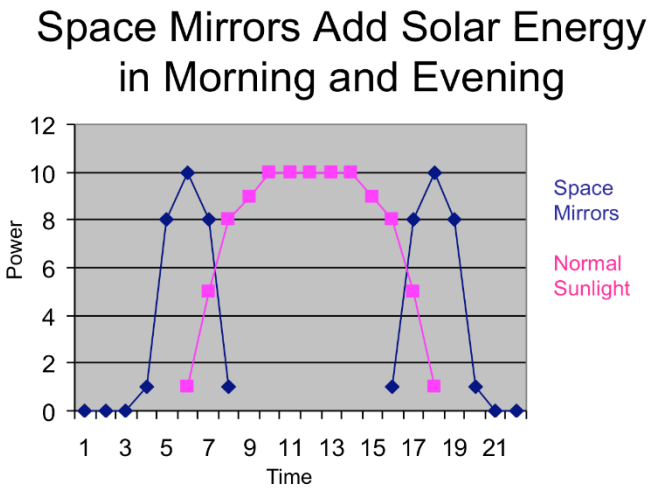
		
This 18 evenly spaced mirror satellite constellation is 1000 km high in a sun synchronous orbit around earth with a 30 degree latitude and longitude view. 30 degree longitude equals 2 hours.	N is up. The circle represents the earth' s surface at 35° latitude. As the world turns, the target ground station moves up and the slant angle and slant range increase. 15° represents 1 hour. When the slant angle is 45°, the earth has turned 13° or 60x13/15 = 52 minutes.	The mirror satellites can be pointed using CMGs as on the International Space Station. Here, the mirror satellites are very simplified and exaggerated in size simply to illustrate a concept.

Space Mirror Size Relative to Fukushima Nuclear Contamination Zone



Contamination Zone around Fukushima Nuclear Power Plant

Space Mirror Array Size or 5 GW Solar Field Size

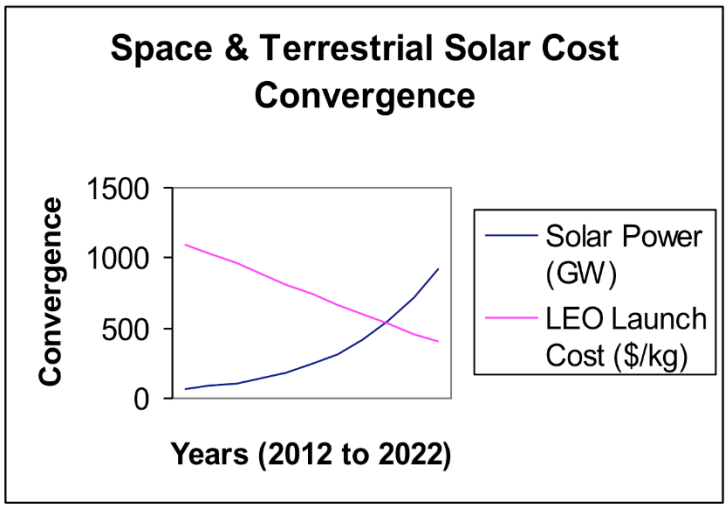


Solar Electric Ground Stations in 2022
(5 GW each PV or trough CSP)

1.) LA, San Diego, S. Ca.	14.) Panama	27.) Calcutta
2.) Hawaii	15.) Rio de Janeiro	28.) Bangkok
3,) Albuquerque	16.) Brasilia	29.) Manila
4.) Phoenix	17.) Lima Peru	30.) Taiwan
5.) Las Vegas	18.) Buenos Aires	31.) Sydney
6.) El Paso	19.) Madrid	32.) Tokyo
7.) Alaska	20.) Rome	33.) Beijing
8.)Calgary	21.) Berlin	34.) Tibet Plateau
9.) Denver	22.) Istanbul	35.) Inner Mongolia
10.) Kansas City, St. Louse	23.) Moscow	36.) Cairo
11.) Miami	24.) South Africa	37.) Delhi
12.) Boston, N.Y., N.J.	25.) Saudi Arabia	38.) Perth.
13.) Mexico City	26.) Bombay	

ECONOMIC CONSIDERATIONS

(Leading to a Business Plan)

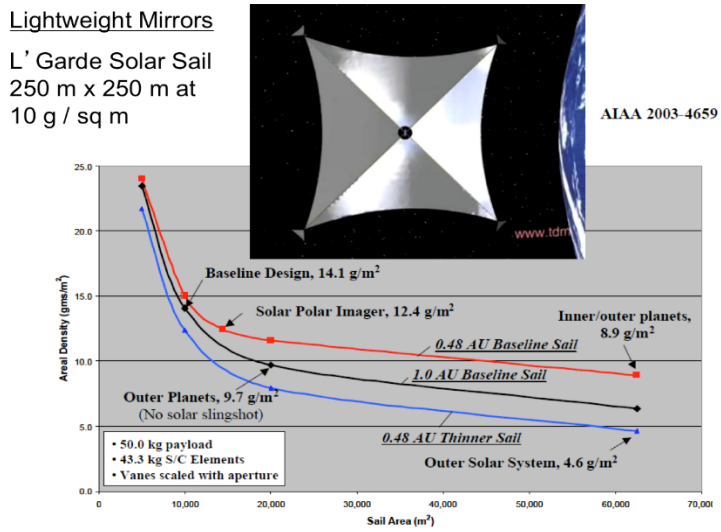


Revenue Projections for Mirror Satellite Constellations

Assumptions - 2022

1) 18 satellites in dawn/dusk orbit 1000 km above earth.
2) The sun's disc diameter viewed from earth is 10 mrad. This implies solar spot size on earth from a mirror up 1000 km equal 1000xtan(10 mrad) = 10 km.
3) Assume each mirror satellites has diameter of 10 km.
4) Solar intensity = 1.37 kW/sq m = 1.37 GW per sq km. If mirrors are at 45 degrees deflecting sunlight 90 degrees toward earth, the beam intensity directed at earth will be 0.95 GW/sq km. The area of each satellite is π x 25 sq km = 78.5 sq km. The energy in the sunlight beamed down toward earth = 75 GW. Assuming slant range losses, the intensity on earth will be 0.7 GW/sq km.

5) **Assuming that an already installed PV array on earth uses 20% efficient modules and has a ground coverage ratio of 50% and occupies an area with a diameter of 10 km equal to the sun beam size, then that ground station will produce 0.7 GW/sq km x 0.1 x 78.5 sq km = 5.5 GW.**
6) **Now assume that in the year 2022 there are 40 ground stations distributed around the world that the 18 satellite constellation will serve and that the constellation gives 1 hr x 0.7 kW/m2 of sunlight to each station in both the morning and in the evening for a total of 2 hr x 0.7 kW/m2 of sunlight per day per station.**
7) **Combined, the 40 earth stations will produce 5.5 x 40 = 220 GW. The total energy produced from the sun beamed satellite constellation = 220 GW x 2 x 365 hrs per year = 160,000 GWh /yr = 1.6 x 10^11 kWh/yr.**
8) **Assume that the price for electricity is $0.1 / kWh, annual revenue = $3x10^10 / yr = $16 billion per yr.**



Mirror Constellation Cost and Payback Time Projections

Mirror Satellite Mass – Inputs The mirror weight on the Ikaros solar sail is 10 g / sq m = 10 metric tons (MT) per sq km. The Billman Power Soletta study assumed a mirror weight of 6 MT per sq km (2). Mass of mirror element, L' Garde estimate (5): 250 m x 250 m mirror sail at 10 g per sq m = 10 MT per sq km. Assume 20 MT per sq km as goal, then each MiraSolar satellite will weigh about 1600 MT.

Mirror Satellite Cost It all depends on launch cost for LEO orbit (Not GEO).The ISC SPS study (4) assumed $400 per kg. SpaceX Falcon Heavy (7) = $1,100 per kg. An AFRL study predicted $250 per kg (8).
MiraSolar sat (4) cost $0.6 B; constellation **(4) $11 B.**
MiraSolar sat (7) cost $1.8 B; constellation **(7) $32 B.**
MiraSolar sat (8) cost **$0.4 B; constellation (8) $7 B.**

Payback time range:

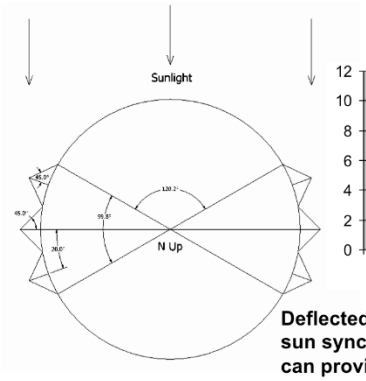
Assuming 40 ground stations and $400 per kg launch cost: 0.7 years.

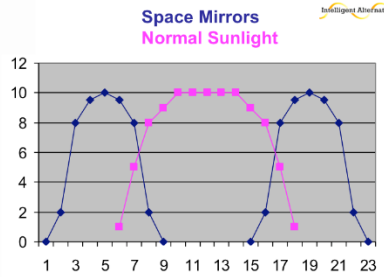
Assuming 40 ground stations and $1100 per kg launch cost: 2 years.

Space power system comparisons

Parameter	Mirror Sat 2022	Soletta 1978	ISC SPS
Orbit	1,000 km	4,200 km	36,000 km
# Satellites	18	10	1
Mirror Area per Sat	78 sq km	462 sq km	12.8 sq km
Total Mirror Area	1404 sq km	4620 sq km	12.8 sq km
24 hr/day Earth Power	40x5.5x2/24 = 18 GW	180 GW	1.2 GW
GW / Mirror sq km	0.012	0.039	0.09
Cost ($400/kg)	$11 B	$110 B	$14 B
$ per 24 h GW	$ 0.7 B / GW	$0.7 B / GW	$11.7 B / GW
Earth Station Size	40x5.5 GW	180 GW	1.2 GW

Longer Term Economics

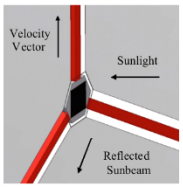




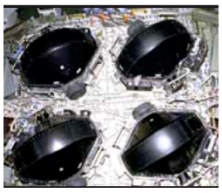
Deflected sun beams from mirrors in sun synchronous dawn to dust low earth orbit can provide 3 hours additional solar energy in early morning and 3 more hours in evenings to ground solar electric power stations reducing the cost of solar electricity to < 6 cents per kWh.

Mirror Satellite Concept
Make one that can be launched today & replicated many times as required

A satellite mirror element is shown with 0.25 km mirror span. The NASA ISC SPS assumes 0.5 km diameter mirrors. This MiraSolar satellite element can serve as an initial test article as well as a repetitive building element.

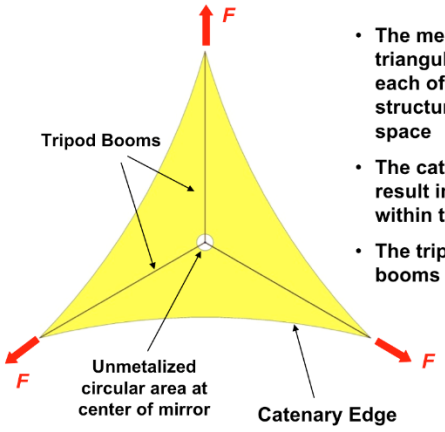


Each mirror satellite consists of lightweight mirror membranes suspended at 3 points by 3 booms telescoping out from a center body. The center body contains CMGs for attitude control and a solar panel for power.



Control Moment Gyros (CMGs) similar to those used on the international Space Station (shown above) can be used to point the mirror satellite at the desired ground solar power station.

DEPLOYED MEMBRANE MIRROR



- The membrane mirror stretched to a triangular configuration by loads *F* at each of the 3 vertices assures a planar structure – 3 points define a plane in space
- The catenary edges (circular arc) result in an isotensoid stress state within the membrane
- The tripod booms are telescoping booms

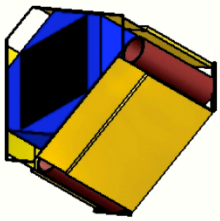
•Boom length = 177 m

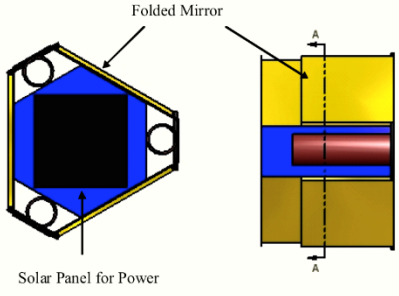
•Triangle side = 307 m

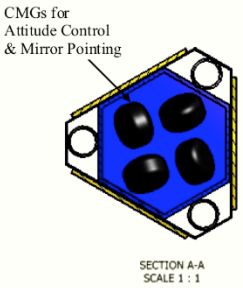
•Mass estimate = 1,250 kg

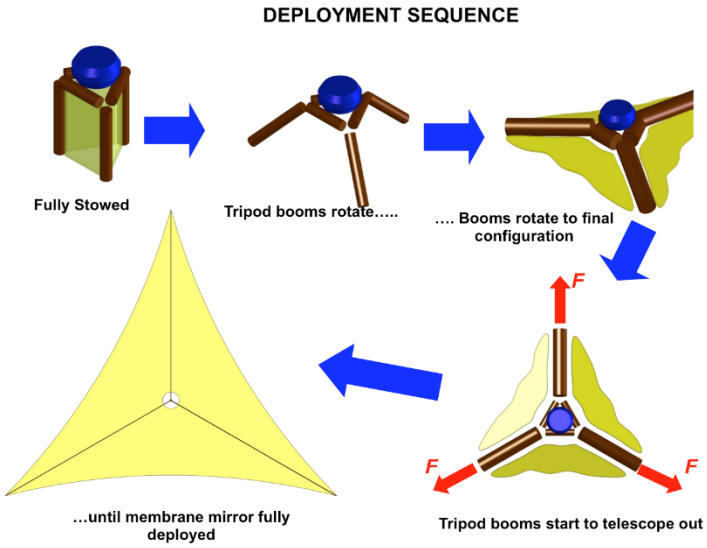
Mirror Satellite in Stowed Form

With booms retracted & mirror folded,
Max diameter = 4.6 m
Height = 3 m
Two can launch with SpaceX Falcon
Four can launch with Delta IV H









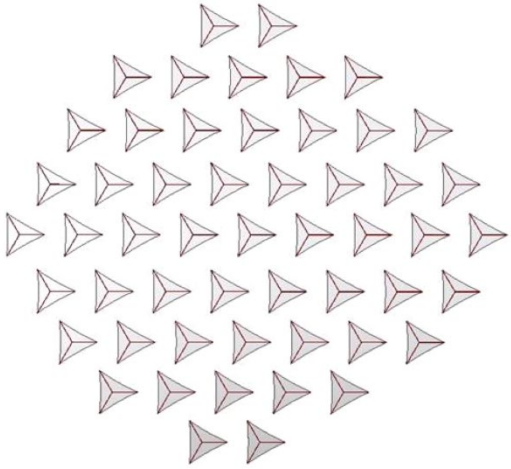
Mirror Satellite Summary

- A specific evolutionary Mirror Satellite Design has been described
- When deployed, the mirror satellite is about twice the size of the International Space Station
- The mirror evolves from the NASA L'Garde solar sail program
- It uses the Control Moment Gyros from the International Space Station for attitude control and mirror pointing. Magnetic Torquers are also useful in polar orbits.
- It folds up so that in compact form, 2 satellites can be launched by SpaceX Falcon or 4 can be launched by Delta IV H.

A Beginning – Space Mirror Moon-Beam Street Lighting

Sun Beam Size	**40 sq miles**
Beam Intensity 250 m diameter space mirror	**62 lumens per m^2 (62 lux)**
Street Light Lamp	**100 W and 20 lux**
Street Light Density in Manhattan	**633 per sq mile**
Electric Power Equivalent per sunbeam site	**633x40x100 = 2.53 MW**
Assume 2 h morning 2 h evening per day	**4x365= 1,460 hrs per year**
Electric Energy per site per year	**3.7 GWhrs per site per year**
Assume $0.1 per kWh	**$0.37 million per site per year**
For 4 sites in US (Miami, Dallas, Denver, LA)	**$1.5 million per year**
For 40 downtown sites around the world	**$15 million per year**
Cost to orbit with SpaceX Falcon [9]	**$3,400 per kg or $3.4 million per MT [9]**
Cost for 20 Mirror Sats at 1 MT per Mirror Sat	**$68 million**
Pay back time for 20 Satellites and 40 sites	**4.5 years**

18 Mirror Satellite Constellation



A Constellation of Mirror Arrays

The NASA TAB 01 for launch vehicles shows a SHLV (super heavy launch vehicle) milestone for 2020 with SHLV defined as >50 MT.

Assuming a mirror array constellation consisting of 18 mirror arrays weighing 1600 MT each, each mirror array will require 32 SHLV (with 50 MT each) launches and the 18 mirror array constellation will then require 18x32 = 576 launches.

Assuming 1 SHLV launch per day, then a first constellation can be assembled in 1.6 years.

Development Road Map & Perspective

Steps	Cost Estimate
1. 1st Mirror Satellite for Moonlight for 4 Disney Parks	$10 Million
2. 18 Mirror Satellites for Municipal Street Lighting	$70 Million
3. 18 Mirror Array Constellation for Ground Solar Farms	$15 Billion
4. 2x18 More Mirror Array Constellations for Solar Farms	$2x11 Billion

Comparison: Three Gorges Dam vs 54 Mirror Array Constellation

Cost:	$37B	$37B
Power (24 hour/day):	22 GW	54 GW
Land Use:	22 GW on 700 sq km	5 GW on 100 sq km

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