SunBeam Space Solar Power Constellation

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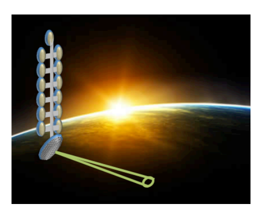
15 December 2011



Solar Satellite Innovation.

1. Introduction

The following proposal details the SunBeam Inc. solution to the Space Solar Power request for proposal (RFP) to provide radio frequency (RF) power downlink to the Solar Max Energy Consortium electric power grids. This proposal will review the system concept to achieve downlink to eight ground sites providing 5GW each by 2026. This system concept features spacecraft design details including choices and analysis of technology, downlink, orbit, satellite design, and space hardening. Proposed downlink site design details are also included. The SunBeam concept will be achieved in three phases each leveraging the lessons of the first and with increasing launch frequency to utilize economies of scale with reduced launch costs. Schedule, timeline, and estimated cost will also be covered in the sections below.

Material in this proposal is proprietary to SunBeam Inc and should be used for proposal evaluation and selection purposes only.

2. System Concept

The SunBeam space solar power constellation will utilize a constellation of 48 satellites to service eight ground downlink sites each with an output of 5GW. The constellation will consist of thirty-two collector and downlink satellites in geosynchronous orbit, four for each downlink site. Since satellites in geostationary orbit (GEO) will fall into earths shadow a constellation of sixteen low earth orbit (LEO) satellites in a sun-synchronous orbit will be used to crosslink energy to the "dark-side" GEO satellites to avoid blackout periods. The system will operate using a 5.8GHz RF-power link for both downlink to ground sites and cross-link from LEO to GEO orbits. Table 1 lists the goal specifications of the SunBeam system. Further details of the system will be described in the remainder of this section.

Table 1. Project Goal Specifications

Specification	Value
Microwave Power Link Frequency	5.8 GHz
DC to RF Conversion	5kW Magnetron MDA (~90% efficiency) [1]
RF to DC Conversion	Rectenna (~85% efficiency) [2]
Solar Radiation to DC	Thin Film Photovoltaic (~46% Efficiency) [3]
Earth Power Downlink Sites	8
Earth Station Power Output	5 GW (each)
Orbit Used	LEO (Collector/Crosslink), GEO (Collector/Downlink)
Number of Satellites Launched	Phase 1: GEO 1st wave satellite launch, assembly, transition to GSO (8 satellites Phase 2: GEO 2nd wave satellite launch, assembly, transition to GSO (24 satellites) Phase 3: Sun Synchronous dark-side harvester launch and assembly (16 satellites)
Time Frame	Phase 1: 2012-2017 Phase 2: 2017-2022 Phase 3: 2022-2030

Orbital Parameters

SUNBEAM proposes to use two orbits to achieve constant RF power downlink to the eight-downlink sites. Each downlink site will have four satellites positioned in geostationary orbit at the closest possible position allowed to maintain safe satellite spacing and maintain geostationary orbit. Since these downlink satellites will fall into the earth shadow, disrupting power to their corresponding downlink sites, a secondary constellation will supply power to the dark-side GEO satellites via an RF crosslink. The crosslink satellites are required to maintain line of sight with the sun at all times, and due to their mission of transferring energy to the GEO satellites for downlink, are required to be larger than their GEO counterparts. Due to the size and orbit parameters required by the crosslink satellites a low earth sun synchronous orbit has been selected. Table 2 contains the relevant parameters of the two satellite constellations.

Table 2. Orbital Parameters

Constellation	Orbit Type	Number Of Satellites	Apogee (km Altitude)	Perigee (km Altitude)	Inclination
LEO "Dark-side" Harvesting & Crosslink	Sun-Synchronous	16 (4/GEO Downlink in earths shadow)	900	900	98°
GEO Bright-side Harvesting & Downlink	Geo-Stationary	32 (4/earth Station)	35786	35786	0°

Figure 1 and 2 illustrate the GEO constellation in both ground track and 3-dimesional representations. Figure 1 depicts GEO satellite grouping positions in green and corresponding earth station sites in red. Figure 2 is a graphical representation generated with AGI STK® featuring eight GEO satellites and resulting downlink beams as pictured at the end of phase 1.

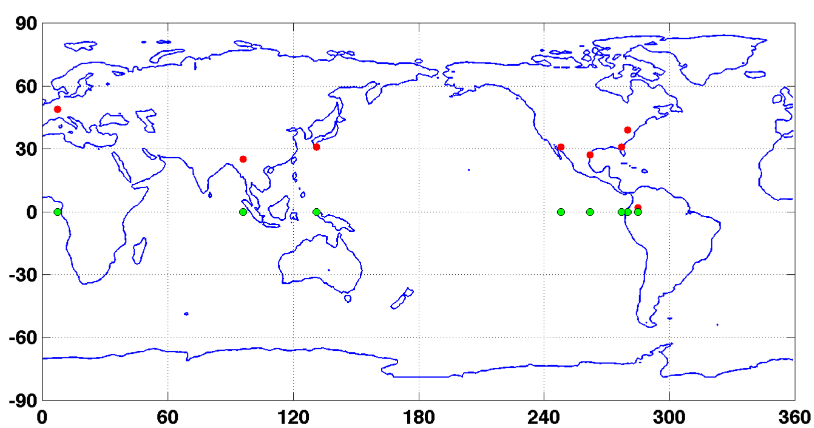


Figure 1. GEO ground track (green) with respective earth stations (red).

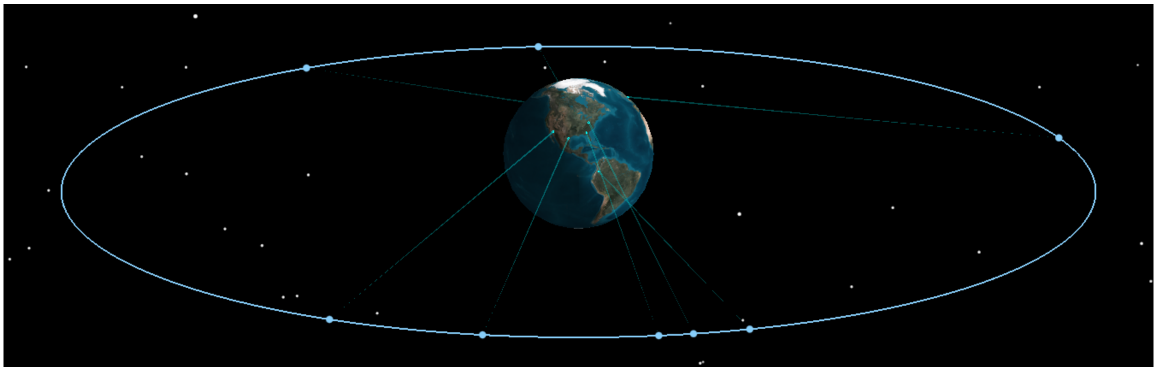


Figure 2. Partial geostationary constellation (phase 1)

Figure 3 and 4 illustrate the LEO constellation in both ground track and 3-dimesional representations. Figure 3 depicts LEO satellite positions in green and corresponding earth station sites in red. Figure 4 contains two graphical representations featuring LEO satellites as pictured during the execution of phase 3.

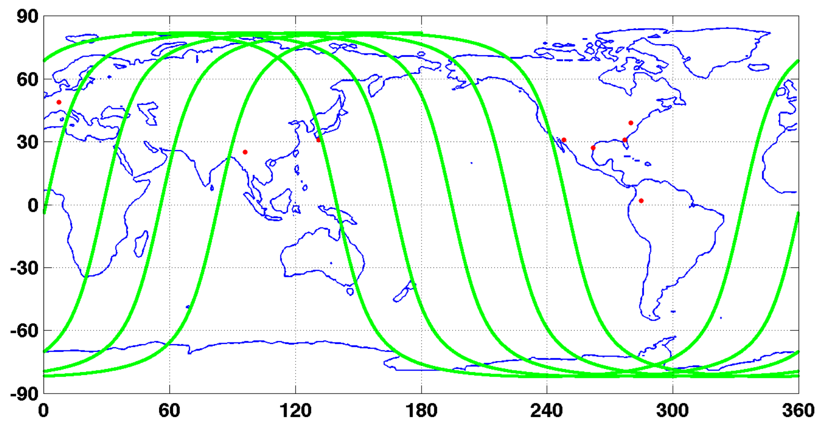


Figure 3. LEO ground track.

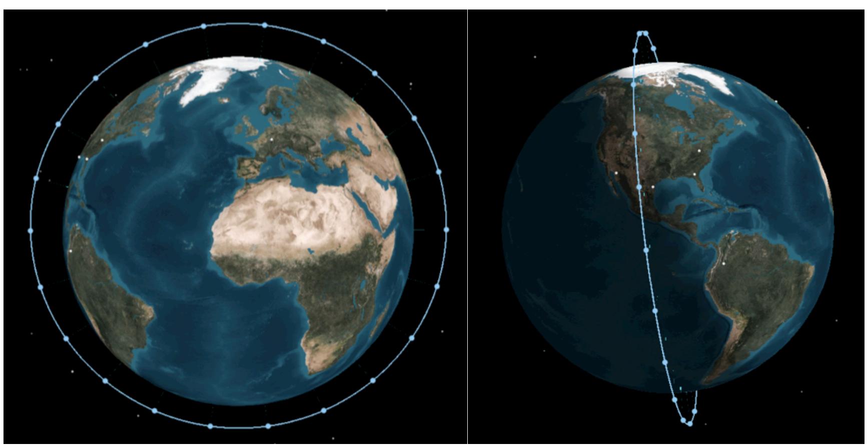


Figure 4. LEO sun-synchronous constellation, 22 satellites shown for visualization purposes (phase 3).

Figure 5 is a graphical representation detailing a possible secondary function of the LEO constellation to downlink power directly during times of peak demand on the bright-side. Due to the large capacity of these satellites this method would be able to downlink similar power to that of the GEO satellites but only for brief periods (several hours) at sunrise and sunset.

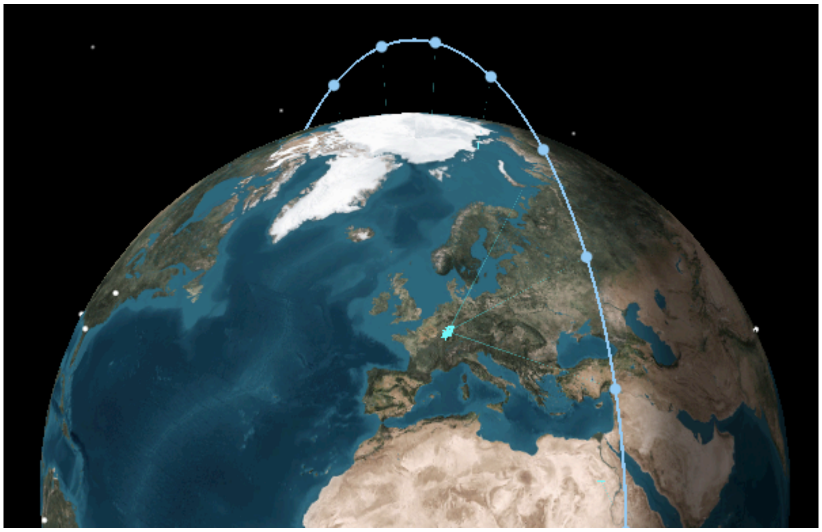


Figure 5. Example LEO Downlink (Phase 3)

Figure 6 is a graphical representation of the SunBeam constellation at the end of phase 3 with GEO satellites downlinking to earth stations and LEO satellites providing cross-link. The image was constructed using only eight GEO satellites and twenty-two LEO satellites to keep from cluttering the image; the full constellation of 48 satellites would be in use at the conclusion of phase 3. Figure 7 is the AGI STK® ground track plot corresponding to the full constellation plot in Figure 6.

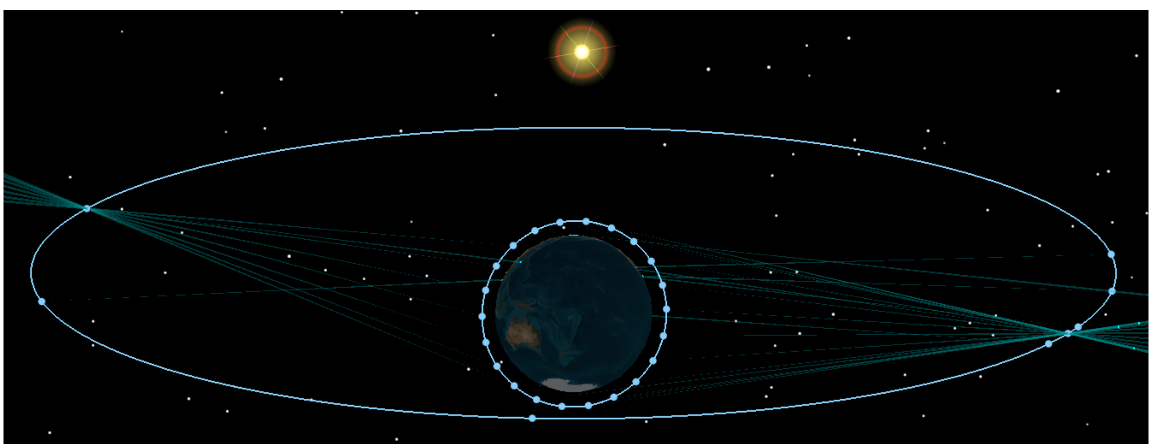


Figure 6. Combined LEO – GEO constellation with
partial dark-side bright-side downlink (Phase 3)

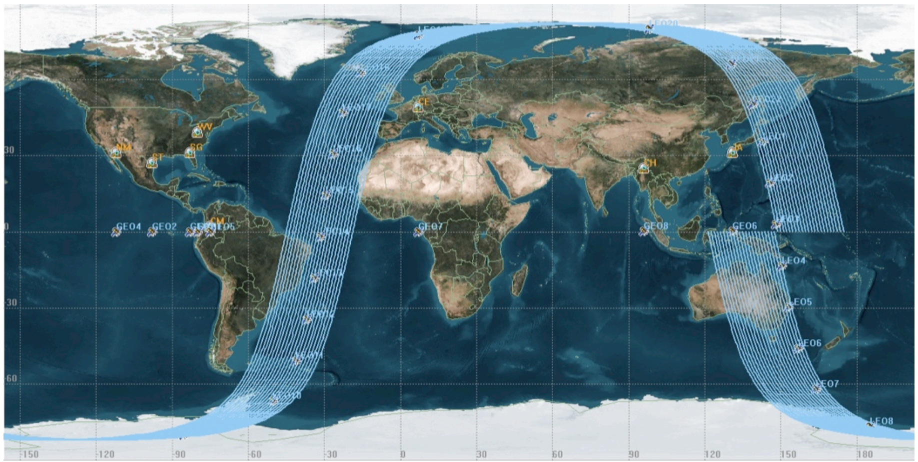


Figure 7. Combined LEO – GEO constellation ground track

Microwave Power Transfer

The SunBeam space solar power constellation utilizes two satellite designs, a GEO solar collector, rectenna, and downlink as well as a LEO solar collector and cross/down link. The GEO satellite design seeks to maximize kW/kg by combining rectenna and solar panel collectors and using high efficiency magnetron phased array. The GEO downlink array will maintain a fixed beam position but have the capability to make beam steering adjustments to optimize downlink. The LEO transmit will be required to steer to the position of the darkside GEO satellite and will receive phasing control from neighboring LEO satellites to avoid spatial nulling on receive. Both LEO and GEO satellites will be assembled in low earth orbit and be towed to their respective orbit locations using high efficiency ion drives.

The GEO satellite, featured in Figure 8, will consist of a large phased array attached to a collector tower. The collector tower will house 200m-diameter collector arrays each covered with thin film photovoltaic (PV) sheets interwoven with rectenna dipole elements. Combining the solar collector and rectenna element will conserve space and weight while retaining the power downlink capability even in earths shadow via the LEO crosslink. SunBeam will subcontract Boeing Spectolab and SolarJunction [3] to produce thin film PV arrays with 46% efficiency. It is expected that rectenna efficiency of 85% can be reached [2]. The phased array will consist of a five-million-element magnetron array similar to the MDA design in [1] yielding the required 120dBW for downlink. An expected efficiency of 90% is the goal for this phased array system. Figure 9 depicts a notional collector array and phased array transmit antenna. Table 3 contains the relevant parameters of the GEO satellite transmitter and the required PV collector area. PV area calculations have been made using an assumed 15% reduction in performance by end of life (EOL).

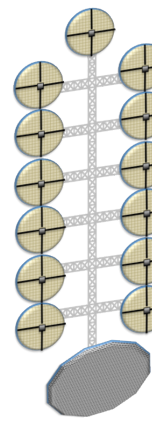


Figure 8. Example GEO satellite featuring large solar collector/Rectenna and downlink transmit array

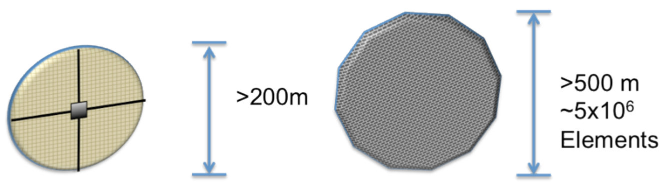


Figure 9. GEO Satellite PV array / Rectenna (left) and downlink phased array (right)

Table 3. GEO Satellite Parameters

GEO Transmitter	Linear	dB
Satellite Systems Power (W)	2000	33.01
Element Power (W)	5000	36.99
Element Gain (dB)	31.62	15
Number of Elements	5.00E+06	66.99
Transmit Chain Loss	1.41	1.5
EIRP (W)	1.12E+12	120.48
Required Power to Operate (W)	2.75E+10	104.39
PV Area Required (m^2)	4.95E+04	

The LEO satellite, featured in Figure 10, will consist of a large phased array attached to a collector tower. The collector tower will house 300m-diameter collector arrays each covered with thin film photovoltaic (PV) sheets. SunBeam will use thin film PV arrays with 46% efficiency, as with the GEO design. The phased array will consist of a one-hundred-million-element magnetron array similar to the MDA design in [1] yielding the required 135.5dBW for cross-link. An expected efficiency of 90% is the goal for this phased array system. Figure 11 depicts a notional collector array and phased array transmit antenna. Table 4 contains the relevant parameters of the LEO satellite transmitter and the required PV collector area. PV area calculations have been made using an assumed 15% reduction in performance by end of life (EOL).

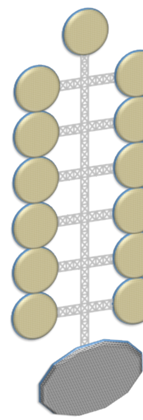


Figure 10. Example LEO satellite featuring large solar collector array and crosslink transmit array

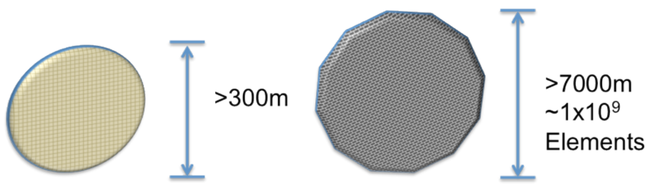


Figure 11. LEO Satellite PV array (left) and link phased array (right)

Table 4. LEO Satellite Parameters

LEO Transmitter	Linear	dB
Satellite Systems Power (W)	2000	33.01
Element Power (W)	5000	36.99
Element Gain (dB)	100.00	20
Number of Elements	1.00E+08	80.00
Transmit Chain Loss	1.41	1.5
EIRP (W)	3.54E+13	135.49
Required Power to Operate (W)	5.50E+11	117.40
PV Area Required (m^2)	1.01E+06	

Table 5 contains the relevant details of the LEO to GEO cross-link path analysis. For calculations the range was taken to the worst case. The driving factors for this link design is to achieve a received power (at GEO satellite) equal to or greater than the required operating power described in Table 3. For space conservation the receive aperture needed on the GEO satellite is also calculated and was kept below that of the required solar collector area. At the worst case, total blackout at GEO and max range, sixteen LEO satellites will be needed to power each darkside GEO downlink. Table 6 contains the various constants and efficiencies used in the tables throughout this section.

Table 5. LEO – GEO Cross Link Parameters

Cross Link		
	Linear	**dB**
Path Length GEO-LEO R (m)	42787639.2	76.31
Path Loss GEO-LEO $(4\pi R/\lambda)^2$ (dB)	1.08211E+20	200.34
Number of Elements	3.6E+12	125.56
Receive Element Gain (dB)	10000	40.00
Transmit Satellites	4	6.02
Receive System Losses	1.412537545	1.50
Receive Power (W)	3.92E+10	105.94
Receive Aperature Area Required (m^2)	4.90E+04	

Table 6. Constants Used for Calculation

CONSTANTS	Linear	dB
Sun Power GEO (W/m^2) [4]	1.39E+06	61.43
Sun Power LEO (W/m^2) [4]	1.36E+06	61.34
Carrier Frequency (Hz)	5.80E+09	97.63
Lambda (m)	0.05	-12.87
η PV	0.46	-3.37
η HPA	0.90	-0.46
η Rectenna	0.85	-0.71
PV EOL Margin	0.15	-8.24

Table 7 lists several enabling technologies needed for the SunBeam system to achieve goal specifications. Listed with each technology are current parameters and future goal parameters, goal parameters are used as the basis for this design.

Table 7. Enabling Technologies

Enabling Technology	Current	Goal
Solar Collector [5] (kw/kg)	1	100
Rectenna [2] (g/m^2)	160	30
MDA Transmit [1] (kW/m^2)	25	200
MDA Transmit [1] (kg/m^2)	35	15

Since weight is the largest driving factor for cost due to the expense of placing material into orbit a brief analysis was completed to assess the estimated mass of each satellite type. Tables 8 and 9 detail the high mass sub-systems and the driving factors for their respective mass.

Table 8. GEO Satellite Mass

Satellite Sub System	Driving Factor	Resulting Weight (kg)
GEO Satellite Power (kW)	2.75E+07	2.75E+05
GEO Rectenna (m^2)	4.90E+04	1.47E+03
GEO Tx MDA (kW)	2.50E+07	1875000
GEO Comm System	-	~100
GEO Control System	-	~100
GEO Framing	-	~1000
Total	**-**	**2.15E+06**

Table 9. LEO Satellite Mass

Satellite Sub System	Driving Factor	Resulting Weight (kg)
LEO Satellite Power (kW)	5.50E+08	5.50E+06
LEO Tx MDA (kW)	5.00E+08	37500000
LEO Comm System		~100
LEO Control System		~100
LEO Framing		~1000
Total		**4.30E+07**

Space Hardening

The SunBeam space solar power constellation will be constructed anticipating the harshest of space environments. Due to the scale and cost of the SunBeam systems it is imperative that all possible steps be taken to ensure the longest component life possible. Three main systems will be considered for hardening; support electronics, collectors, and high power transmit system. The SunBeam satellites will house all support system electronics in a shielded containers to reduced the effects of radiation and protect against high velocity particles. Solar collectors will be constructed with radiation hardening and scratch resistance in main focus along with weight and efficiency. The SunBeam system design has incorporated a 15% end of life reduction increasing the total area to compensate for degradation and damage over time. The transmit system is perhaps the most robust considering the relative durability of magnetron based amplifiers and slot arrays. The transmit array will be made with the most durable material possible to avoid damage due to high velocity particles. Radiation shielding will be used to prevent damage to magnetron based MDAs caused by excess radiation.

Earth Station Design

The SunBeam space solar power system will service eight earth station sights each with an output capacity of 5GW starting in 2026, capacity will be guaranteed to 99.99% climate conditions starting in 2030. The following section will describe the notional design of the SunBeam earth station and the eight ground stations. Table 7 features the locations of the eight proposed sites as well as their range from each constellation, climate characteristics, and resulting rectenna field size. Figure 12 depicts the locations of each site on a world map.

Table 10. Earth Station Locations

Earth Station	Latitude	Longitude	Nominal Range to GEO Downlink (km)	Rain Climate Zone [7]	Peak Rainfall (99.99% in mm/hr) [7]	Rectenna Field (km^2)
West Virginia	39° N	80° W	37400	K	42	6.06
South Texas	27° N	98° W	36600	M	63	6.66
South Georgia	31° N	83° W	36800	M	63	6.71
North Mexico	31° N	112° W	36800	E	22	5.41
Columbia	2° N	75° W	35800	N	95	7.92
Japan	31° N	131° E	36800	M	63	6.71
Central Europe	49° N	7° E	37500	H	32	5.78
Myanmar	25° N	96° E	36500	N	95	8.08

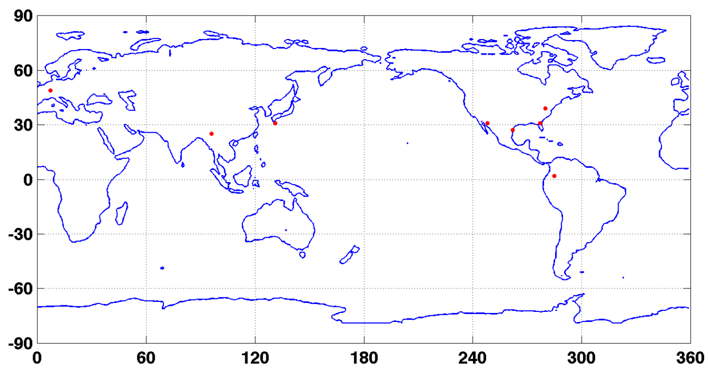


Figure 12. Earth station locations (red).

Two characteristics drive the the size of the each earth station and the resulting cost of power, predicted rain rate and range to GEO. To assess the impacts of these parameters of the proposed earth stations a graph was constructed to evaluate the areas requiring the largest recetenna arrays. Figure 13 depicts the predicted rain rate and range to GEO for each site. Figure 14 shows the resulting required rectenna array sizes for each site. A link analysis for each earth station can be found in Appendix 1.

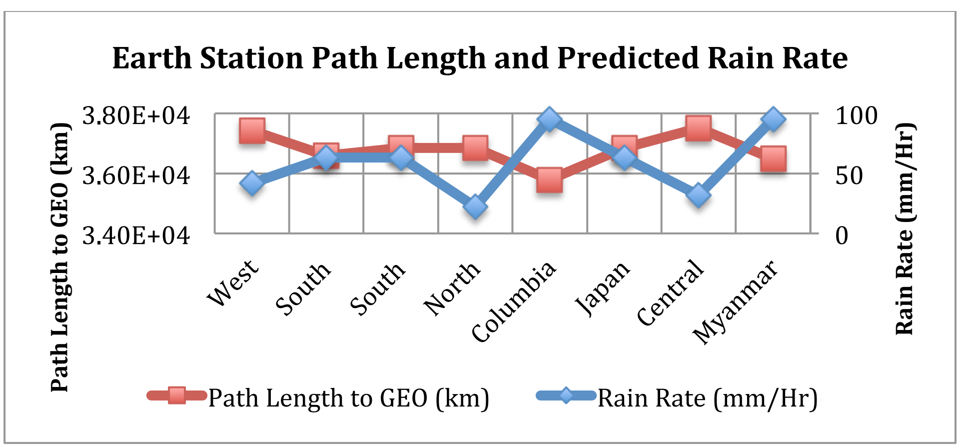


Figure 13. Earth station predicted rain rate and path length to GEO.

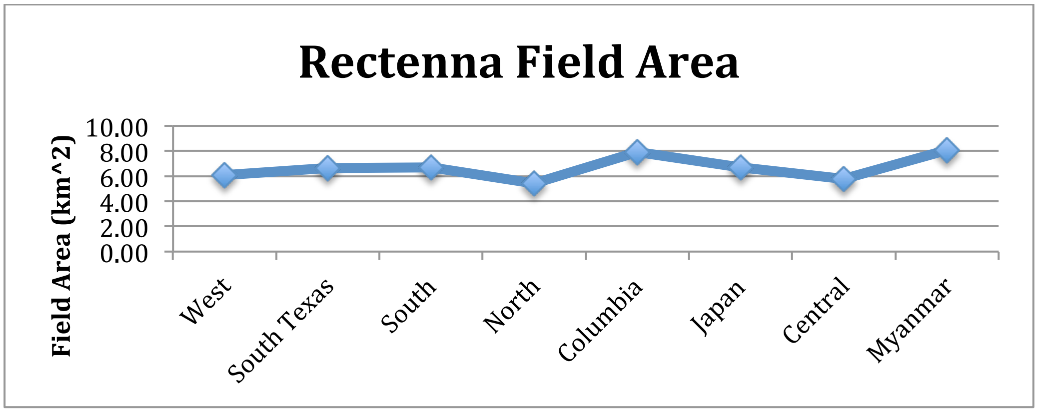


Figure 13. Earth station required rectenna field size.

Each ground station should be constructed with a rectenna field size specified in Table 7 using SunBeam rectenna array sub-arrays linked in parallel. Figure 14 depicts the SunBeam sub array design featuring 1000 6dB gain patch antenna elements connected to a Silicon Schottky diode quad bridge with high reverse breakdown voltage as in [2].

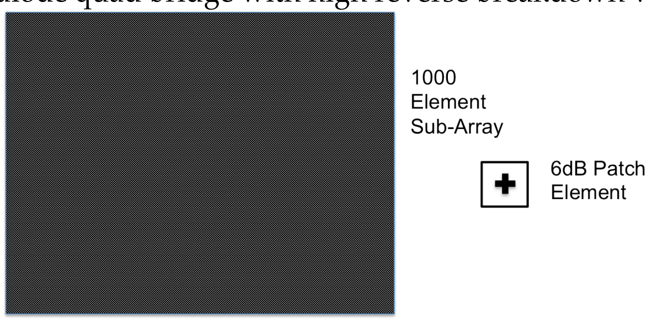


Figure 14. SunBeam rectenna sub-array and 6dB patch element (not to scale)

Communication & Control System

The SunBeam space solar power constellation will require constant secure communications to maintain control structure for crosslink and downlink. Precise positioning and antenna position information is critical for link performance. Absolute and guaranteed privacy, authenticity, and reliability are required due to the infrastructure tied to the output of each space power station.

The communication network will take a two-stage approach to controlling the complex space solar power constellation. Ground stations will each have direct link with a master GEO satellite directly via a 35GHz RF link. Since the ground stations will not have line of sight to the LEO constellation the GEO satellites will provide a relay for this constellation across 60GHz data link. The GEO to ground link will employ high gain antennas at each location minimizing the opportunity for signal intercept outside of the power station. The 60GHz will have inherent anti-intercept properties in that any listening device must be outside of the earth's atmosphere due to the severe atmospheric attenuation at 60GHz [7]. GEO satellites will be organized in a master slave configuration with one satellite having a link to the earth station and the others being slaved via 60GHz links to the master. Both links will be encoded with low density parity check encoding to assure maximum error tolerance and will be encrypted using a randomized key symmetric encryption scheme using AES-256 for symmetric encryption block coding and RSA for key exchange and authentication. Waveforms will be modulated with a spreading code to reduce probability of intercept and utilize code division multiple access protocol to allow each ground station and satellite a unique spreading code.

3. Estimated Budget and Timeline

The proposed timeline for the SunBeam system and a cost analysis are presented in this section with the goal of output capacity of 5GW for eight earth stations starting in 2026, guaranteed full capacity by 2030. The development and execution effort will consist of three phases. The first phase will occur for five years after award with the goal of developing, launching, and completing the master GEO satellites for each of the eight earth stations. Phase 2 will occur for the following five years with the goal of completing the GEO constellation (four GEO satellites per earth station). The third and final phase will occur over the following eight years and will add the thirty-two LEO satellites to assure uninterrupted 24hour power downlink. Several factors will be considered for costing purposes including launch costs, personnel, materials and equipment, as well as supplies and miscellaneous expenses. Table 11 describes the current and projected future launch costs as well as sites and flight requirements. Figure 13 graphs launch costs from 2012-2030 based on the proposed timeline and anticipated launch costs.

Table 11. Launch Cost Outline

Launch Platform	Payload Mass (kg)	Launch Site	Cost/kg	Year Available	Required Flights / Year
Falcon Heavy	53000 [8]	Cape Canaveral AFS	$2,358.49	2013	N/A
Falcon 9 LEO	10450 [9]	Cape Canaveral AFS or Kwajalein	$5,741.63	2013	N/A
Falcon 9 GTO	4540 [9]	Cape Canaveral AFS or Kwajalein	$13,215.86	2013	N/A
Gen 2 ($100/Lb) >3162 flights/year (after 5 years)	53000	Kwajalein	$220.46	2017	>3162
Gen 3 ($60/Lb) >3162 flights/year (after 10 years)	53000	Kwajalein	$132.28	2022	>3162

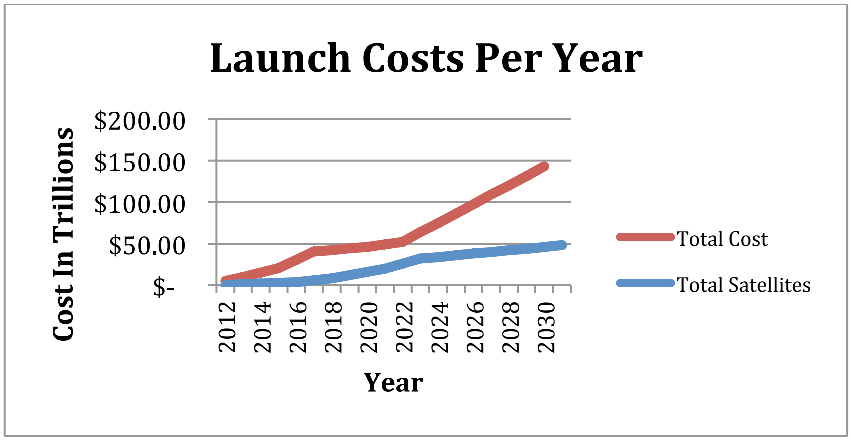


Figure 13, Graph of anticipated launch costs based on proposed design and timeline.

A full cost report is outlined in Table 12 featuring estimated costs of labor, equipment, launch costs, and other expenses. Labor and materials were computed using a cost per satellite schedule budgeting for 200 million for materials and equipment and 1000 man-years for each satellite as well as small budgets for supplies as miscellaneous expenses.

Table 12. Proposed Budget (all figures in millions)

Year	Labor	Materials & Equipment	Supplies	Launch Costs	Misc	Total/Year	Total Cost
2012	$208.80	$200.00	$0.05	$5,077.05	$0.50	$5,486.40	$5,486.40
2013	$208.80	$200.00	$0.05	$10,154.11	$0.50	$10,563.46	$16,049.86
2014	$208.80	$200.00	$0.05	$15,231.16	$0.50	$15,640.51	$31,690.38
2015	$208.80	$200.00	$0.05	$20,308.22	$0.50	$20,717.57	$52,407.94
2016	$417.60	$400.00	$0.10	$30,462.33	$0.50	$31,280.53	$83,688.47
2017	$417.60	$400.00	$0.10	$40,616.44	$0.50	$41,434.64	$125,123.11
2018	$835.20	$800.00	$0.20	$42,514.77	$0.50	$44,150.67	$169,273.77
2019	$835.20	$800.00	$0.20	$44,413.10	$0.50	$46,049.00	$215,322.77
2020	$835.20	$800.00	$0.20	$46,311.43	$0.50	$47,947.33	$263,270.10
2021	$1,252.80	$1,200.00	$0.30	$49,158.93	$0.50	$51,612.53	$314,882.63
2022	$1,252.80	$1,200.00	$0.30	$52,006.42	$0.50	$54,460.02	$369,342.65
2023	$417.60	$400.00	$0.10	$63,382.59	$0.50	$64,200.79	$433,543.44
2024	$417.60	$400.00	$0.10	$74,758.76	$0.50	$75,576.96	$509,120.40
2025	$417.60	$400.00	$0.10	$86,134.93	$0.50	$86,953.13	$596,073.53
2026	$417.60	$400.00	$0.10	$97,511.10	$0.50	$98,329.30	$694,402.84
2027	$417.60	$400.00	$0.10	$108,887.27	$0.50	$109,705.47	$804,108.31
2028	$417.60	$400.00	$0.10	$120,263.44	$0.50	$121,081.64	$925,189.95
2029	$417.60	$400.00	$0.10	$131,639.61	$0.50	$132,457.81	$1,057,647.76
2030	$417.60	$400.00	$0.10	$143,015.78	$0.50	$143,833.98	$1,201,481.75

Using an average wholesale kWHr price derived from the SolarMax RFP of approximately $0.15 and reduction of 10% starting after 6 years an estimate of revenue can be computed.

Figure 14 graphs this estimated revenue with the aggregate cost of the SunBeam system. It is evident that due to the front-end cost of this system and the low wholesale energy prices the system will not have a break-even point before 2030. Additional revenue details can be found in Appendix 2.

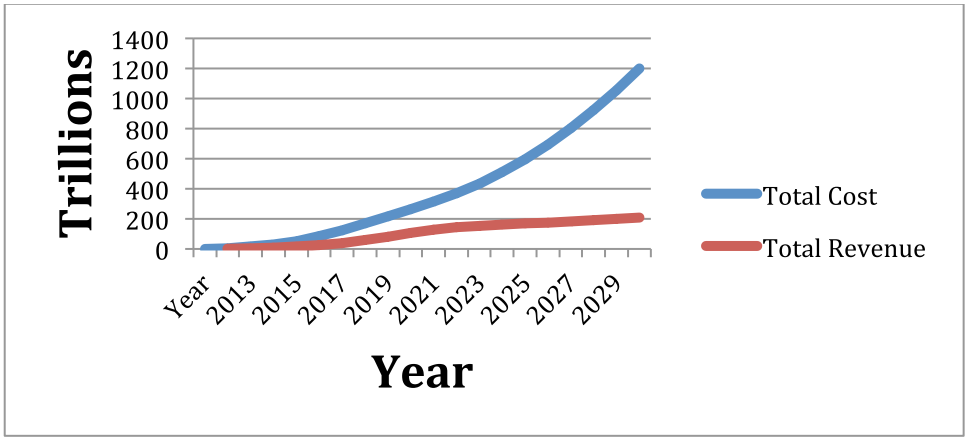


Figure 14, Graph of anticipated revenue (based on average kWHr price in RFP) with estimated total cost.

If the Solar Max Energy Consortium intends on recovering costs of design and deployment at or before 2030 a higher kWHr price will have to be considered. Figure 15 illustrated the yearly kWHr price needed to break even on each year's expenditures.

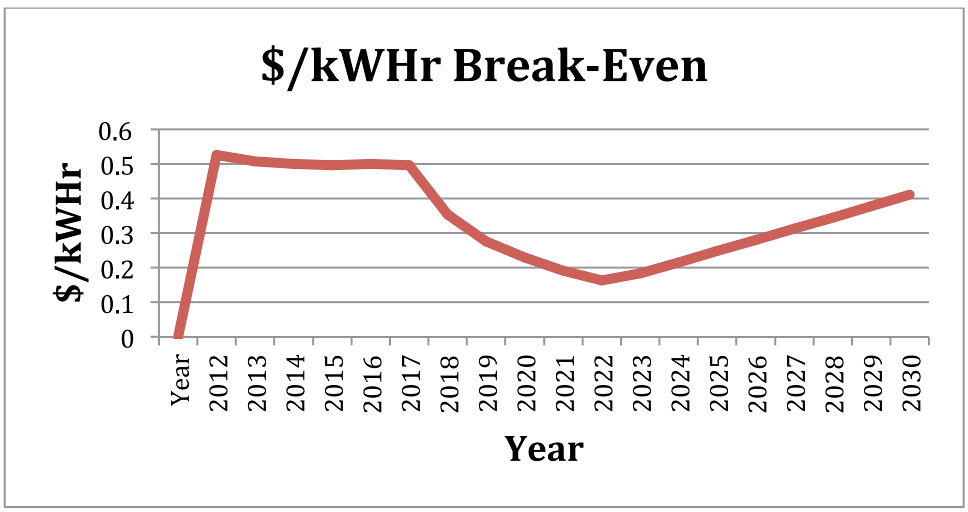


Figure 15, Graph of kWHr pricing needed to break even on each year's development and deployment costs.

3. References

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Appendix 1. Link Loss Analysis Results

Downlink SITE:	West Virginia	
	Linear	dB
Site Latitude	39	
Path Length to GEO R (m)	3.74E+07	75.73
Path Loss GEO $(4\pi R/\lambda)^2$ (dB)	8.27785E+19	199.18
N GEO Satellites	4	6.02
Path Length to LEO (m)	5935000.27	67.73
Path Loss LEO $(4\pi R/\lambda)^2$ (dB)	2.08198E+18	183.18
N LEO Satellites	8	9.03
Site 0.01% Rainfall (mm/Hr)	42	
γ_R Specific Attenuation (dB/km)	-	0.15
Path Attenuation Rain (dB)	-	1.53
Receive Chain Loss (dB)	1.41	1.5
Rectenna Element Gain (dB)	3.98	6
Number of Elements	5.50E+16	167.40
Rectenna Field Size (m^2)	6.06E+06	
Receive Power GEO (W)	5.00E+09	96.99
Receive Power LEO (W)	1.26E+14	141.00

Downlink SITE:	South Texas	
	Linear	dB
Site Latitude	27	
Path Length to GEO R (m)	3.66E+07	75.63
Path Loss GEO $(4\pi R/\lambda)^2$ (dB)	7.91588E+19	198.98
N GEO Satellites	4	6.02
Path Length to LEO (m)	7176490.30	68.56
Path Loss LEO $(4\pi R/\lambda)^2$ (dB)	3.0441E+18	184.83
N LEO Satellites	8	9.03
Site 0.01% Rainfall (mm/Hr)	63	
γ_R Specific Attenuation (dB/km)	-	0.25
Path Attenuation Rain (dB)	-	2.54
Receive Chain Loss (dB)	1.41	1.5
Rectenna Element Gain (dB)	3.98	6
Number of Elements	6.65E+16	168.23
Rectenna Field Size (m^2)	6.66E+06	
Receive Power GEO (W)	5.01E+09	97.00
Receive Power LEO (W)	8.26E+13	139.17

Downlink SITE:	**South Georgia**	
	Linear	**dB**
Site Latitude	31	
Path Length to GEO R (m)	3.68E+07	75.66
Path Loss GEO $(4\pi R/\lambda)^2$ (dB)	8.02346E+19	199.04
N GEO Satellites	4	6.02
Path Length to LEO (m)	6770103.49	68.31
Path Loss LEO $(4\pi R/\lambda)^2$ (dB)	2.7091E+18	184.33
N LEO Satellites	8	9.03
Site 0.01% Rainfall (mm/Hr)	63	
γ_R Specific Attenuation (dB/km)	-	0.25
Path Attenuation Rain (dB)	-	2.54
Receive Chain Loss (dB)	1.41	1.5
Rectenna Element Gain (dB)	3.98	6
Number of Elements	6.74E+16	168.29
Rectenna Field Size (m^2)	6.71E+06	
Receive Power GEO (W)	5.01E+09	97.00
Receive Power LEO (W)	9.41E+13	139.73

Downlink SITE:	**North Mexico**	
	Linear	**dB**
Site Latitude	31	
Path Length to GEO R (m)	3.68E+07	75.66
Path Loss GEO $(4\pi R/\lambda)^2$ (dB)	8.02346E+19	199.04
N GEO Satellites	4	6.02
Path Length to LEO (m)	6770103.49	68.31
Path Loss LEO $(4\pi R/\lambda)^2$ (dB)	2.7091E+18	184.33
N LEO Satellites	8	9.03
Site 0.01% Rainfall (mm/Hr)	22	
γ_R Specific Attenuation (dB/km)	-	0.07
Path Attenuation Rain (dB)	-	0.68
Receive Chain Loss (dB)	1.41	1.5
Rectenna Element Gain (dB)	3.98	6
Number of Elements	4.39E+16	166.42
Rectenna Field Size (m^2)	5.41E+06	
Receive Power GEO (W)	5.00E+09	96.99
Receive Power LEO (W)	9.39E+13	139.73

Downlink SITE:	**Columbia**	
	Linear	**dB**
Site Latitude	2	
Path Length to GEO R (m)	3.58E+07	75.54
Path Loss GEO $(4\pi R/\lambda)^2$ (dB)	7.57132E+19	198.79
N GEO Satellites	4	6.02
Path Length to LEO (m)	9508459.32	69.78
Path Loss LEO $(4\pi R/\lambda)^2$ (dB)	5.34385E+18	187.28
N LEO Satellites	8	9.03
Site 0.01% Rainfall (mm/Hr)	95	
γ_R Specific Attenuation (dB/km)	-	0.42
Path Attenuation Rain (dB)	-	4.23
Receive Chain Loss (dB)	1.41	1.5
Rectenna Element Gain (dB)	3.98	6
Number of Elements	9.40E+16	169.73
Rectenna Field Size (m^2)	7.92E+06	
Receive Power GEO (W)	5.01E+09	97.00
Receive Power LEO (W)	4.50E+13	136.53

Downlink SITE:	**Japan**	
	Linear	**dB**
Site Latitude	31	
Path Length to GEO R (m)	3.68E+07	75.66
Path Loss GEO $(4\pi R/\lambda)^2$ (dB)	8.02346E+19	199.04
N GEO Satellites	4	6.02
Path Length to LEO (m)	6770103.49	68.31
Path Loss LEO $(4\pi R/\lambda)^2$ (dB)	2.7091E+18	184.33
N LEO Satellites	8	9.03
Site 0.01% Rainfall (mm/Hr)	63	
γ_R Specific Attenuation (dB/km)	-	0.25
Path Attenuation Rain (dB)	-	2.54
Receive Chain Loss (dB)	1.41	1.5
Rectenna Element Gain (dB)	3.98	6
Number of Elements	6.74E+16	168.29
Rectenna Field Size (m^2)	6.71E+06	
Receive Power GEO (W)	5.01E+09	97.00
Receive Power LEO (W)	9.41E+13	139.73

Downlink SITE:	**Central Europe**	
	Linear	**dB**
Site Latitude	40	
Path Length to GEO R (m)	3.75E+07	75.74
Path Loss GEO $(4\pi R/\lambda)^2$ (dB)	8.31314E+19	199.20
N GEO Satellites	4	6.02
Path Length to LEO (m)	5828715.08	67.66
Path Loss LEO $(4\pi R/\lambda)^2$ (dB)	2.00808E+18	183.03
N LEO Satellites	8	9.03
Site 0.01% Rainfall (mm/Hr)	32	
γ_R Specific Attenuation (dB/km)	-	0.11
Path Attenuation Rain (dB)	-	1.09
Receive Chain Loss (dB)	1.41	1.5
Rectenna Element Gain (dB)	3.98	6
Number of Elements	5.00E+16	166.99
Rectenna Field Size (m^2)	5.78E+06	
Receive Power GEO (W)	5.01E+09	96.99
Receive Power LEO (W)	1.31E+14	141.19

Downlink SITE:	**Myanmar**	
	Linear	**dB**
Site Latitude	25	
Path Length to GEO R (m)	3.65E+07	75.62
Path Loss GEO $(4\pi R/\lambda)^2$ (dB)	7.86724E+19	198.96
N GEO Satellites	4	6.02
Path Length to LEO (m)	7376627.94	68.68
Path Loss LEO $(4\pi R/\lambda)^2$ (dB)	3.21625E+18	185.07
N LEO Satellites	8	9.03
Site 0.01% Rainfall (mm/Hr)	95	
γ_R Specific Attenuation (dB/km)	-	0.42
Path Attenuation Rain (dB)	-	4.23
Receive Chain Loss (dB)	1.41	1.5
Rectenna Element Gain (dB)	3.98	6
Number of Elements	9.77E+16	169.90
Rectenna Field Size (m^2)	8.08E+06	
Receive Power GEO (W)	5.01E+09	97.00
Receive Power LEO (W)	7.77E+13	138.91

Appendix 2. Additional Financial Analysis

Table A2.1 Estimated Yearly Revenue

Year	ES Power Output (GW)	Up Time / Day	kWHr/ Year	Avg. Wholesale Price of kWHr	Revenue	Total Rev
2012	1.25	22.83	10417708333	0.1571	$1,637,068,452.38	$1,637,068,452.38
2013	2.5	22.83	20835416667	0.1571	$3,274,136,904.76	$4,911,205,357.14
2014	3.75	22.83	31253125000	0.1571	$4,911,205,357.14	$9,822,410,714.29
2015	5	22.83	41670833333	0.1571	$6,548,273,809.52	$16,370,684,523.81
2016	7.5	22.83	62506250000	0.1571	$9,822,410,714.29	$26,193,095,238.10
2017	10	22.83	83341666667	0.1571	$13,096,547,619.05	$39,289,642,857.14
2018	15	22.83	1.25013E+11	0.1571	$19,644,821,428.57	$58,934,464,285.71
2019	20	22.83	1.66683E+11	0.1414	$23,573,785,714.29	$82,508,250,000.00
2020	25	22.83	2.08354E+11	0.1131	$23,573,785,714.29	$106,082,035,714.29
2021	32.5	22.83	2.7086E+11	0.0792	$21,452,145,000.00	$127,534,180,714.29
2022	40	22.83	3.33367E+11	0.0475	$15,841,584,000.00	$143,375,764,714.29
2023	40	24	3.504E+11	0.0238	$8,325,504,000.00	$151,701,268,714.29
2024	40	24	3.504E+11	0.0238	$8,325,504,000.00	$160,026,772,714.29
2025	40	24	3.504E+11	0.0238	$8,325,504,000.00	$168,352,276,714.29
2026	40	24	3.504E+11	0.0238	$8,325,504,000.00	$176,677,780,714.29
2027	40	24	3.504E+11	0.0238	$8,325,504,000.00	$185,003,284,714.29
2028	40	24	3.504E+11	0.0238	$8,325,504,000.00	$193,328,788,714.29
2029	40	24	3.504E+11	0.0238	$8,325,504,000.00	$201,654,292,714.29
2030	40	24	3.504E+11	0.0238	$8,325,504,000.00	$209,979,796,714.29

Table A2.2 Break Even kWHr Prices by Year

Year	kWHr/ Year	Total/Year	$/kWHr
2012	10417708333	$5,486,404,472.57	$0.53
2013	20835416667	$10,563,458,945.13	$0.51
2014	31253125000	$15,640,513,417.70	$0.50
2015	41670833333	$20,717,567,890.26	$0.50
2016	62506250000	$31,280,526,835.39	$0.50
2017	83341666667	$41,434,635,780.53	$0.50
2018	1.25013E+11	$44,150,666,737.51	$0.35
2019	1.66683E+11	$46,048,997,694.50	$0.28
2020	2.08354E+11	$47,947,328,651.49	$0.23
2021	2.7086E+11	$51,612,525,086.98	$0.19
2022	3.33367E+11	$54,460,021,522.46	$0.16
2023	3.504E+11	$64,200,791,712.61	$0.18
2024	3.504E+11	$75,576,961,902.76	$0.22
2025	3.504E+11	$86,953,132,092.91	$0.25
2026	3.504E+11	$98,329,302,283.05	$0.28
2027	3.504E+11	$109,705,472,473.20	$0.31
2028	3.504E+11	$121,081,642,663.35	$0.35
2029	3.504E+11	$132,457,812,853.50	$0.38
2030	3.504E+11	$143,833,983,043.65	$0.41