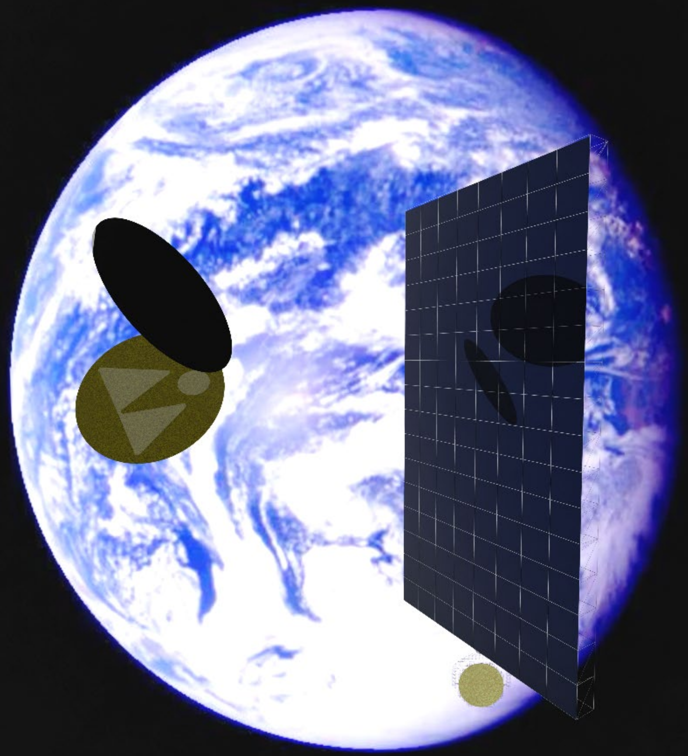
Survey of Space Based Solar Power (SBSP)



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Survey of Space Based Solar Power (SBSP)
A Comparison of SBSP Reference Designs and their Economics

Overview

Over the past decade, Space Based Solar Power (SBSP) – the use of satellites to capture solar energy and transmit it wirelessly to receiving stations on the ground as a clean, firm power source – has received a fresh look. Since the influential 1980 NASA report on SBSP was released, the cost for placing payloads into orbit has dropped by a factor of at least one hundred. These costs are expected to continue declining over the next decade (see *Appendices*). Steadily advancing semiconductor technology, embedded computation, advanced materials, robotic automation, and reusable rockets have greatly reduced the required orbital mass and cost of space solar power systems. The 1980 NASA proposal was never realized. Its development and deployment costs were estimated at over three trillion dollars, adjusted for inflation, with a program timeline covering 26 years. In the past four years, various government and commercial entities, including Virtus Solis, have presented detailed design proposals that have been deemed technically and economically feasible for near future deployment. In this white paper, published data of these studies is compiled and compared. Seven competing system architectures are reviewed to provide a survey of the state of the art of SBSP designs and their economics.

The key design parameters of these architectures are presented. To provide consistent evaluation, the Levelized Cost of Energy (LCOE) is calculated given common assumptions. Additional assumptions needed in the analysis are identified and stated. The analysis ignores the upfront costs of Research and Development (R&D), but does compare costs associated with constructing an operational power plant at original scale and amortization period as well as at a normalized 1.5 GW-level with a 20 year finance life. Costs for the orbital power plant, associated ground stations, and financing, operating and maintenance, manufacturing margin and space launch are included. On-orbit robotic assembly of the plants is assumed, but in-space manufacturing of the satellite materials is not -all materials are assumed to be manufactured on and launched from Earth.

This study concludes that SBSP can be an economically competitive contributor to the world's energy mix. The technical and safety viability of SBSP with low associated carbon emissions were established in multiple prior studies and is outside the scope of this analysis. Applications for SBSP include grid-connected customers and point loads such as data centers, green hydrogen generation, desalination, and other high-power customers. As shown, most SBSP systems described herein could provide energy at a competitive price in today's market and future markets. The Virtus Solis architecture excels, with an LCOE of $25/MWh.

SBSP System Architectures

This architectural study considers and summarizes results for seven SBSP systems. The work of earlier studies, performed by government and private entities, is leveraged. These references are cited as they occur. Data associated with the Virtus Solis system was internally generated.

Throughout, data from earlier studies is provided for reference. To ensure consistency across architectures for comparison, this study provides an adjusted value for many parameters. Assumptions associated with these adjustments are provided throughout, including adjusting for inflation and currency.

As an example, regardless of the launch vehicle cited in previous studies, the adjusted values within this study assume the same launch vehicle for all approaches; in this case, the SpaceX Starship/Super Heavy to Low Earth Orbit (LEO). Further, the number of required refueling missions to achieve adequate payload to either Medium or Geosynchronous Earth Orbit (MEO/GEO) is adjusted in a consistent manner across approaches, assuming the use of passive cooling techniques to minimize boil-off for cryogenic propellant/oxidizer storage on-orbit (see *Appendices*).

NASA's Solar Power Satellite System (1980)

NASA launched studies of SBSP throughout the 1970s, culminating in the Solar Power Satellite Definition Study which ran from 1977 through 1980. The system was to consist of sixty 5GW satellites in GEO beaming power to ground stations at 2.45MHz[1]. Materials would be launched to LEO and transferred via Orbital Transfer Vehicles (OTVs) to GEO where they would be assembled into satellites by a team of space workers.

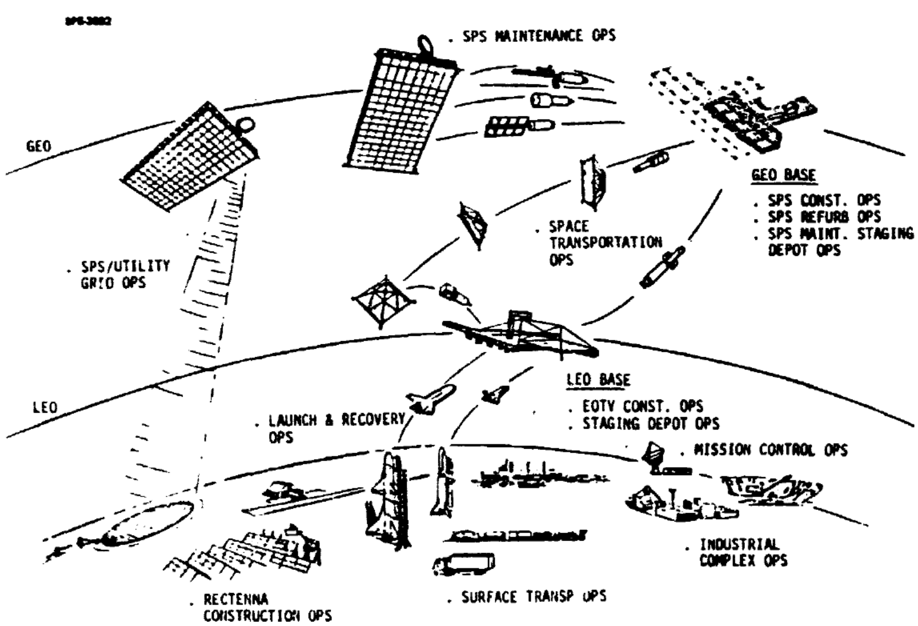

Figure 1 - NASA Integrated SPS Program Operations (Courtesy NASA)

The implementation of the SPS system would have required the development of four dedicated launch vehicles and the establishment of a crew base in LEO and in GEO. Klystron tubes were preferred over solid state devices for microwave transmission; each satellite would have required 101,552 klystrons to transmit 6.7GW. In 1977 dollars, the cost for the first satellite was estimated at $102B[2], with subsequent satellites costing $11.2B each, for a total of $762B (roughly $3.3 trillion in 2024 dollars) to deliver 300 GW to ground stations..

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[1] Solar Power Satellite System Definition Study, Final Report for Phase III, Volume 1: Executive Summary. NASA-CR-160742, Boeing Aerospace Co., D180-25969-1, June 1980.

[2] Ronald J. Harron and Richard C Wadle (Lyndon B. Johnson Space Center), Solar Power Satellite Cost Estimate, NASA Technical Memorandum 58231, January 1981

Fraser-Nash's CASSEOPeiA (2022, sponsored by ESA)

Proposed in 2016, the CASSEOPeiA satellite is a 'constant aperture' design, where the solar collection aperture and the power transmission aperture stay the same, independent of the satellite position in orbit. This constant aperture approach results in a system with no moving parts, with solar collection constantly oriented toward the Sun and WPT beaming steering to track ground targets.

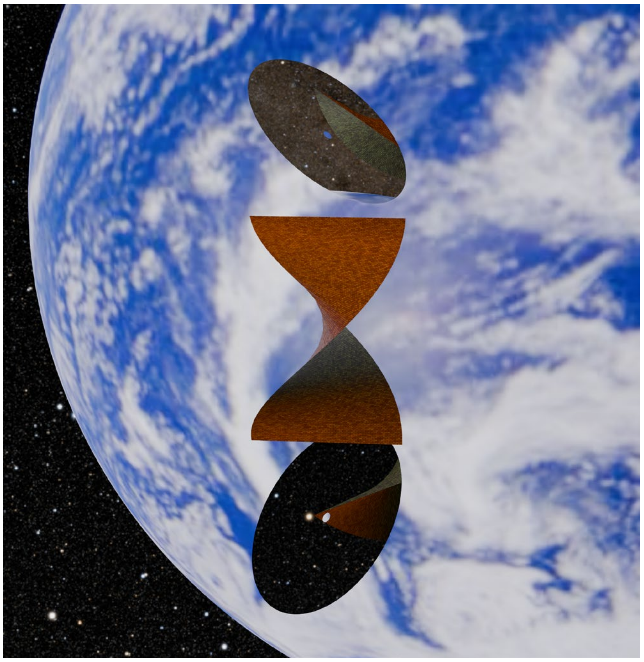


Figure 2 - Frazer Nash Reference Design

Two novel aspects of the design are the use of triplets of antennas which steer an RF beam over 360 degrees, and a 3-dimensional organization of the antenna triplets that presents a constant area (a.k.a aperture) when viewed from a target on earth. This combination of elements enables a constant power level of solar power collection and transmission power to a receiver on earth.

The ESA Fraser-Nash study analysis focused on the development, deployment, and operation of this satellite in GEO orbit with an 18 year development timeline to commercial operation.

Roland Berger's Architecture (2022, sponsored by ESA)

The Roland Berger/2022 ESA architecture is based on the SPS-Alpha design. Mirrors are used to redirect and concentrate the solar power onto a receiving structure, which incorporates the power beaming hardware. The mirrors move to track the sun to maximum power generation throughout the orbit.

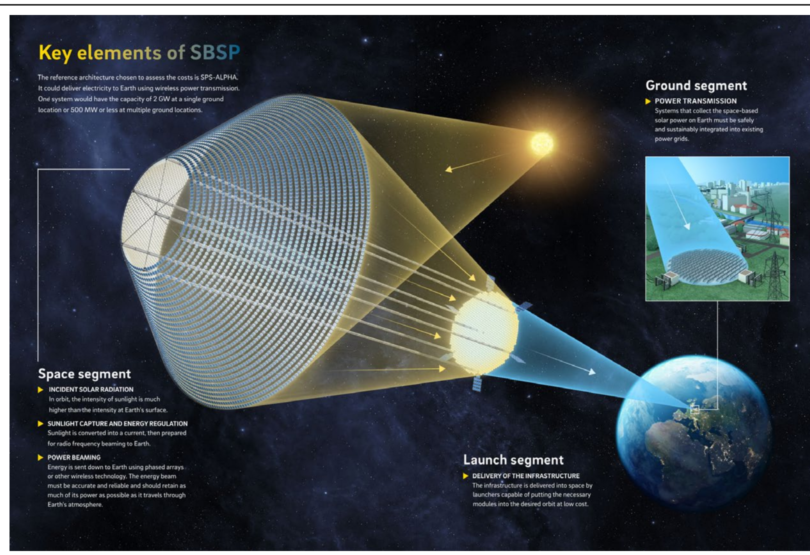


Figure 3 - Roland Berger/SPS Alpha Concept (Courtesy ESA)

Thales Alenia's SBSP Pre-Phase A System Study (2023, sponsored by ESA)

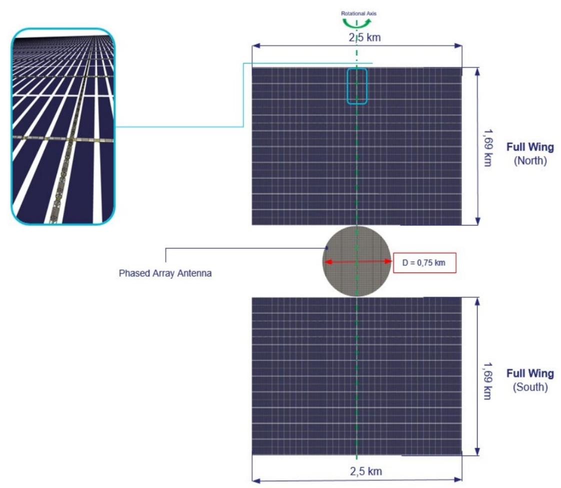


Figure 4 - Thales Alenia SBSP Pre-Phase A System (Courtesy ESA)

The Thales Alenia Pre-Phase A Study System incorporates key elements from the 1980 NASA/Boeing reference system. There is a transmitter which rotates with respect to the solar panels to maximize the solar power collection and the antenna aperture with respect to a ground receiver.

The power from the solar array is aggregated into a high power bus. All of the solar power must pass through a rotating joing between the solar array and the transmitter.

NASA's Reference Design One "Innovative Heliostat Swarm" / SPS-ALPHA Mark III (2024)

In January 2024, NASA's Office of Technology, Policy and Strategy released a study intended to assess the current state of SBSP and to offer direction for NASA's future efforts in the area. The study, titled *Space Based Solar Power*[3], focused on two parameters – cost and greenhouse gas (GHG) emissions – and analyzed two different reference designs against these parameters. For both reference designs, NASA assumed the decade of the 2030s would be spent in design and the 2040s in implementation – launches to LEO followed by transfer to and assembly in GEO. With these assumptions, first power would be received on the ground in 2050.

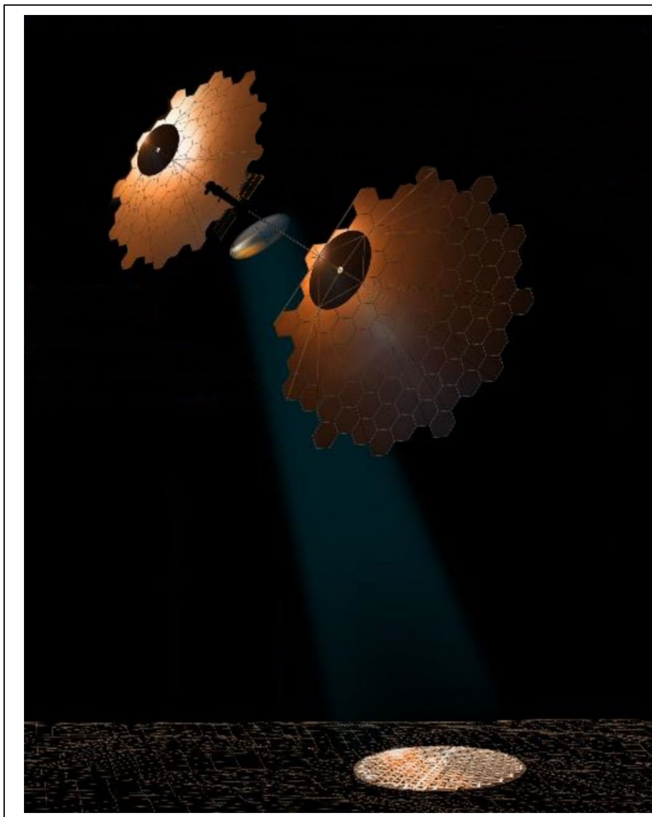


Figure 5 - NASA Reference Design #1 Heliostat Swarm Concept (courtesy NASA)

While the study assumed that technologies required to realize SBSP systems would be feasible in the near term, the assumptions used in the cost and GHG analyses assumed little or no cost benefit from economies of scale, innovation, and the reliability of modern space electronics. NASA also assumed no effort during the 2020s--an excessively lengthy interval for design and for implementation--and does not consider

[3] Rogers et al. "Space Based Solar Power," NASA Report ID 20230018600, January 11, 2024

overlap between design, implementation, and the start of power delivery. Therefore, we take exception to the costs generated within the NASA study. Here, we study the two reference designs and provide an independent analysis of the costs using reasonable economic benefit assumptions.

The first of the two reference designs considered, Innovative Heliostat Swarm, appears to be heavily derived from SPS-ALPHA Mark III. Mark III is an evolved version of the SPS-ALPHA concept developed by former NASA engineer Dr. John Mankins and granted NIAC funding in 2011.

As stated by Dr. Mankins, "SPS-ALPHA incorporates a number of critical new technologies, including: (1) wireless power transmission using a retro-directive RF phased array with high-efficiency solid-state amplifiers; (2) high-efficiency multi-band gap photovoltaic solar cells, employed in a concentrator PV architecture with integrated thermal management; (3) lightweight structural components, applied in various systems and subsystems; (4) autonomous robotics in a highly structured environment; and (5) a high degree of autonomy among individual modules. SPS-ALPHA involves three major functional elements: (1) a large primary array that is nadir pointing; (2) a very large sunlight-intercepting reflector system involving a large number of reflectors that act as individually pointing "heliostats," mounted on a non-moving structure; and (3) a truss structure that connects those two. As conceived, SPS-ALPHA is not a traditional three-axis stabilized satellite with one or more solar arrays; rather, SPS-ALPHA entails body mounted (non-moving) solar power generation on a gravity-gradient stabilized satellite, with an axis-symmetric physical configuration.[4]"

NASA's Reference Design Two "Mature Planar Array" / Tethered-SPS (2024)

The second reference design considered by NASA for the January 2024 study, Mature Planar Array, appears to be based on a system known as Tethered-SPS. This approach was proposed in the early 2000's by a group from the Japan Aerospace Exploration Agency (JAXA) led by Susumu Sasaki.

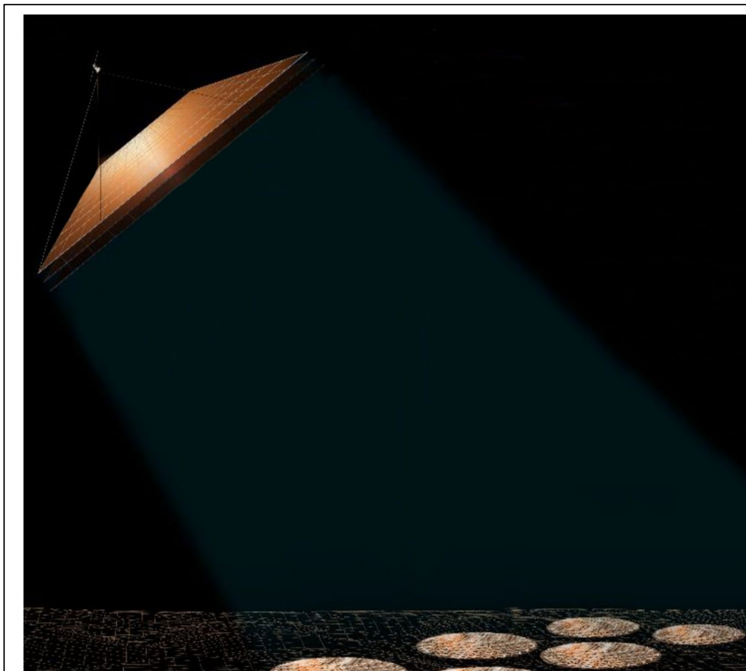


Figure 6 - NASA Reference Design #2 - Mature Planar Array Concept (Courtesy NASA)

As described in a June 2022 publication, Tethered-SPS is an array of modular unit cells called tiles that individually collect solar energy and transmit it to Earth from GEO. From a June 2022 publication[5], "Sunlight is collected via lightweight parabolic concentrators and converted to DC electric power with high efficiency III-V photovoltaics. CMOS integrated circuits within each tile generate and control the phase of multiple independently-controlled microwave sources using the DC power. These sources are coupled to multiple radiating antennas which act as elements of a large phased array to beam the RF power

[4] John C. Mankins, "SPS-ALPHA: A Novel Approach to Space Solar Power," Ad Astra (magazine publication of NSS), Volume 25, Number 1, Spring 2013

[5] Pellegrino et al. "A lightweight space-based solar power generation and transmission satellite." (2022) https://doi.org/10.48550/arXiv.2206.08373.

to Earth. The power is sent to Earth at a frequency chosen in the range of 1-10 GHz and collected with ground-based rectennas... ...the resulting satellite has no movable parts once it is fully deployed."

Virtus Solis' Lucidus Hyper-Modular Architecture (2023)

Virtus Solis's approach to SBSP is to assemble near-gossamer arrays of meter-scale monolithic "tile" satellites into highly elliptical ground synchronous Molniya orbits which feature long dwell times over a given site on the Earth's surface. The thin "tile" architecture includes PV on one face, power electronics, communications and control in a center layer and WPT phased-array antennas (PAAs) on the opposite face. A co-orbiting modular gossamer mirror adjacent to each array ensures that the satellite's solar collectors receive sunlight continuously by rotating about the array's normal axis once per year. Wireless power transfer is accomplished via integrating the satellite tiles into kilometer-scale PAAs operating at 10GHz. Each array can dynamically track ground stations through 11-1/2h or more of each 12h orbital period and at sufficient scale can deliver power to multiple ground stations simultaneously. Each array serves two sets of ground stations separated by 160-200deg of longitude sequentially every other orbit, and a constellation of two or more arrays can provide firm power with 2h of ground energy storage at each ground station. As new ground stations are established, either additional arrays on new ground tracks can be added to the constellation or existing arrays can be scaled up to serve increases in demand (about 20GW maximum per array). Using this hyper-modular approach, system capacity can scale up by gigawatts annually with greater than 320GW planned deployment by 2040.

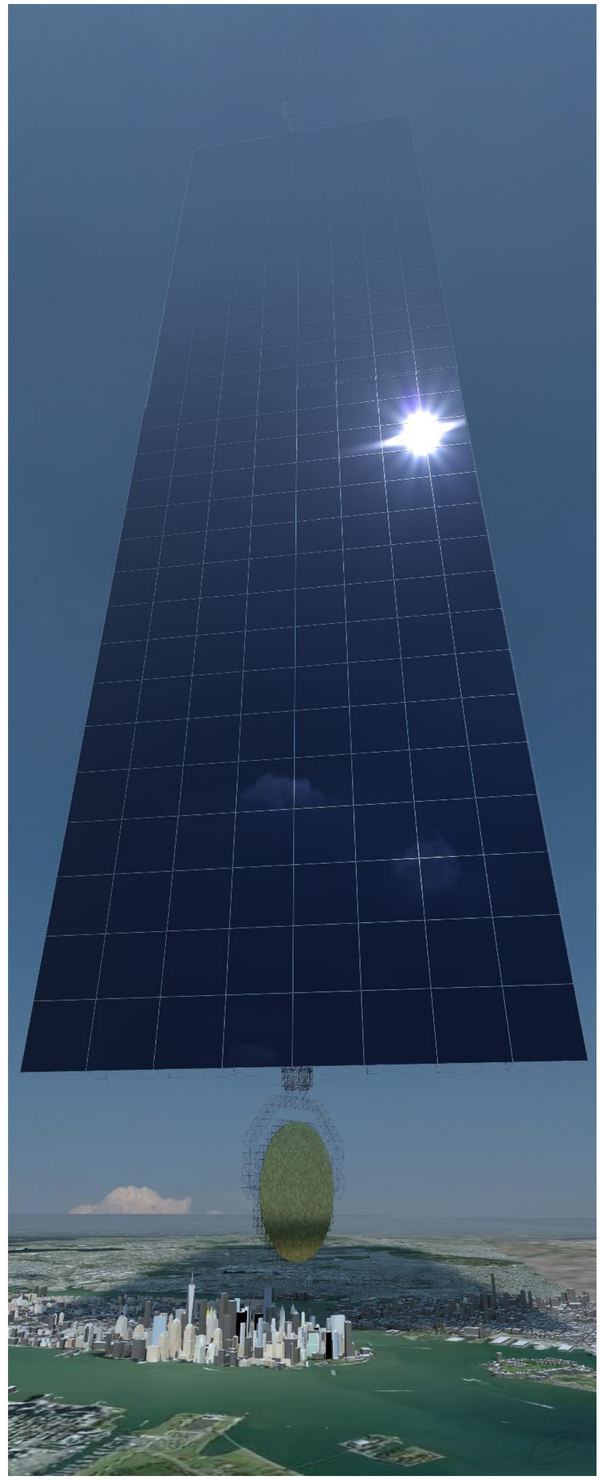


Figure 7 - 1980 NASA 10 GW SBSP Satellite compared to Manhattan

A constellation of three or more arrays can provide ground stations 100% coverage with redundancy – reducing the need for battery storage at scale. The planned constellation of 16 arrays can provide redundant baseload power anywhere on Earth simultaneously to hundreds of ground stations. To reach Molniya orbits, use of Starship with refueling in LEO is assumed (see *Appendix I*). Variants of the Lucidus architecture can be deployed to

GEO, but Virtus Solis believes interoperability with GEO telecom satellites would push SBSP deployments out decades and is not the primary path..

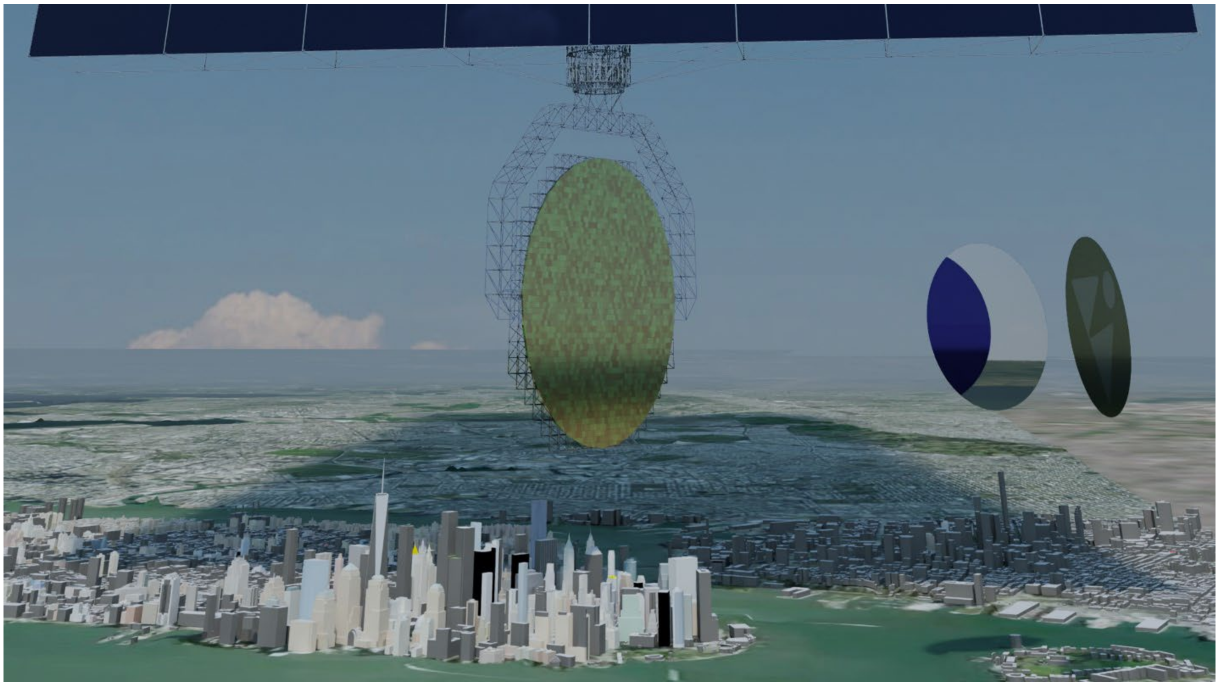


Figure 8 - Virtus Solis 200MW Lucidus compared to 1980 NASA Reference Design Antenna & Manhattan

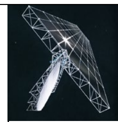
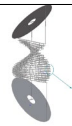
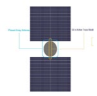
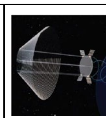
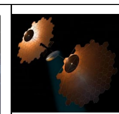
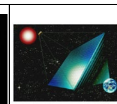
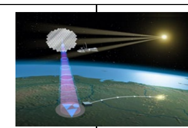
Methodology

Each architecture's data was extracted from their reference publications and binned in appropriate categories. Research and Development costs were segregated from construction, launch and operation costs and presented LCOE is tabulated if available. As large power plants are constructed using project finance, large variations in these assumptions as well as other boundary conditions make significant impacts to the cost of the energy produced. To help normalize the architectures, we scaled the specifications to reach 1.5GW delivered to the ground and calculated the Levelized Cost of Energy (LCOE) assuming 20y finance period with 13% hurdle rate, using a common launch vehicle to help compare the cost efficiency of the core architecture assumptions (R&D costs are excluded from LCOE). The reference launch vehicle is the SpaceX Starship/Super Heavy whose costs are estimated as described in *Appendix I*. Vehicles with greater in-space transport cost efficiency (known as an Orbital Transfer Vehicle (OTV)) may ultimately be available in the timeframe of these architectures, but those costs are unknown at the time of writing and it may be that economies of scale of reusable chemical rockets avoid the need for OTVs in cislunar space.

Parametric Comparison of SBSP Architectures

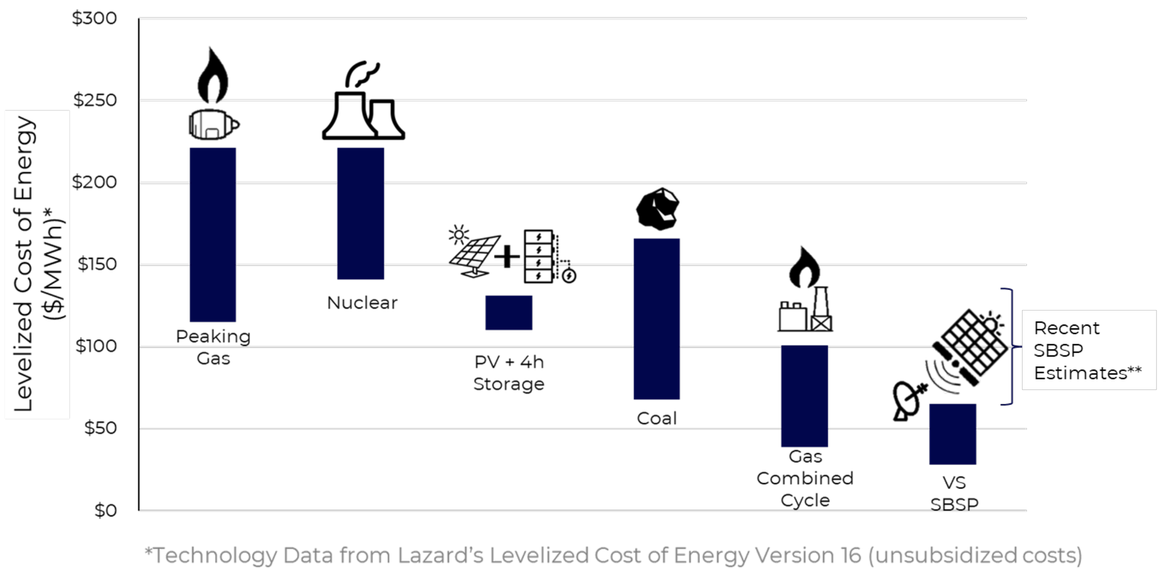
The table that follows summarizes the key attributes of the different SBSP systems previously described and compares the costs of electricity under common modeling assumptions.

Table 1 - Summary of SBSP Concept Parameters and Performance

									
		NASA-Boeing Phase III 1980	**Frazer Nash ESA 2022**	**Thales Alenia ESA 2023**	**Roland Berger ESA 2022**	**NASA RD1 Competitive 2024**	**NASA RD2 Competitive 2024**	**Virtus Solis - Project #1**	**Virtus Solis - Project #8**
Rated Power to Grid	**MW**	2500	1440	1007	2000	2000	2000	200	8,000
Orbit Type		GEO	GEO	GEO	GEO	GEO	GEO	MEO - Molniya	MEO - Molniya
Capacity factor		99%	99%	99%	90%	100%	60%	89%	89%
Annual energy produced	MWh	21,681,000	12,488,256	8,733,107	15,768,000	17,467,440	10,512,000	1,559,280	62,371,200
Total Mass	metric tons	21,020	2,064	6,640	6,877	5,900	10,000	732	24,513
Major Dimensions	m	5,000 x 10,000	4,000 x 1,700 ø	2,500 x 4,130	4,500 x 3,300 ø	4,500 x 3,300 ø	2,000 x 1,900	967 ø	5,596 ø
Area of Reflector	m^2	N/A	6,450,000.00	N/A	8,310,000.00		N/A	1,397,425	46,816,431
Area of PV	m^2	21,800,000	7,940,000	6,200,000	2,710,000			734,098	24,593,701
Area of WPT	m^2	1,580,000	2,990,000	440,000	3,030,000	2,269,801	3,800,000	734,098	24,593,701
Energy yield lifetime									
Amorized Lifetime	years	30	30	30	30	30	30	20	20
Generation Type		Simple PV	Concentrated PV	Simple PV	Concentrated PV	Concentrated PV	Simple PV	Simple PV	Simple PV
Photovoltaic Efficiency		40%	40%	24%	31%	35%	35%	31%	31%
PV Concentration Factor		3.00	625	1.00	3.00	2-3	1.00	1.00	1.00
Wireless Power Transmission (WPT)									
Frequency microwave radiation	GHz	2.45	2.45	2.45	5.80	2.45	2.45	10.0	10.0
Transmitting Antenna									
DC-RF efficiency		80%	74%	78%	80.1	70%	70%	85%	85%
Atmospheric attenuation		98%	99%	98%	98%	98%	98%	95%	95%
Freespace transmission efficiency		50%	77%	75%	82%	84%		100%	100%
Effective Radius of Transmitter	m	709	976	374	982	850	1,100	483	2,798
Receiving Antenna (Rectenna)									
Efficiency RF-DC		89%	82%	82%	87%	95%	95%	92%	92%
Efficiency DC-AC		97%	95%	94%	96%	90%	90%	99%	99%
Radius of Rectenna	m	3,350	3,150	2,735	3,350	3,000	4,000	1,000	2,178
Rectenna Area	m^2	35,256,524	31,172,453	23,499,820	35,256,524	28,274,334	50,265,482	3,140,000	14,900,000
Ground Station Battery Energy Storage									
Storage Duration	h	N/A						2.00	2.00
Unit cost battery (x hour)	$/kWh							$172.00	$172.00
Cost	$ million							$66.00	$2,652.00
Estimated Costs									
Spacelift	$ million	$2,166	$2,464	$3,310	$5,658	$32,595	$55,800	$264	$3,235
Launch Vehicle		Boeing Arch. (Space Freighter)	Reaction Engines Skylon	Not Identified	SpaceX Starship	SpaceX Starship	SpaceX Starship	SpaceX Starship	SpaceX Starship
Launch specific cost	$/kg	$103	$1,194	$498	$823	$5,525	$5,580	$361	$132
Total Capex	$ million	$87,217	$4,537	$4,456	$16,315	$49,017	$73,465	$695	$9,689
Project Finance Hurdle rate		13%	13%	13%	13%	13%	13%	13%	13%
Manufacturer's Margin		15%	15%	15%	15%	15%	15%	15%	15%
Stated LCOE	**$/MWh**	N/A	$ 63.64	$ 143.00	$ 108.53	$ 30.00	$ 80.00	$ 74.64	$ 25.40
LCOE (Calculated)	**$/MWh**	$ 226.02	$ 68.67	$ 93.15	$ 109.81	$ 52.96	$ 88.73	$ 74.64	$ 25.40
Normalized 1.5GW LCOE	**$/MWh**	$ 480.71	$ 54.33	$ 58.36	$ 116.50	$ 94.66	$ 107.38	$ 39.47	$ 25.82

CONCLUSION

Levelized Cost of Energy is a way to evaluate competing energy generation technologies but is inadequate if the generation is not firm (capacity available when needed). As SBSP is a generation and transmission technology in one with the capability to be fully firm, it obviates the need for long distance transmission, long duration energy storage or demand management – which must be accounted for when compared to non-firm, intermittent energy. Lazard's regularly publishes green-field generation and energy storage costs, and the analyzed SBSP architectures presented in this study are all at the low end of the range of Lazard's technology costs. This analysis validates Virtus Solis's contention that SBSP is a clean, firm, low-cost and therefore scalable energy technology to solve the world's energy needs.



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Virtus Solis Technologies, Inc.

Virtus Solis Technoeconomic Model, December 5th, 2023

APPENDICES

APPENDIX I – LAUNCH ECONOMICS OF SPACEX STARSHIP/SUPER HEAVY

Mission design is a large aspect of deployment of SBSP. In the near term, only well-characterized launch vehicles can provide appropriate boundary conditions for launch integration. SBSP in particular requires up-mass in the hundreds to thousands of tonnes for a single orbital power generation plant. As chemical rockets are largely propellant, the major parameters describing their performance are the specific impulse of the rocket engines, their thrust-to-weight ratio and the vehicle structural/dry mass fraction. As structural mass per unit volume of propellant decreases with scale, larger rockets have increasingly better performance metrics.

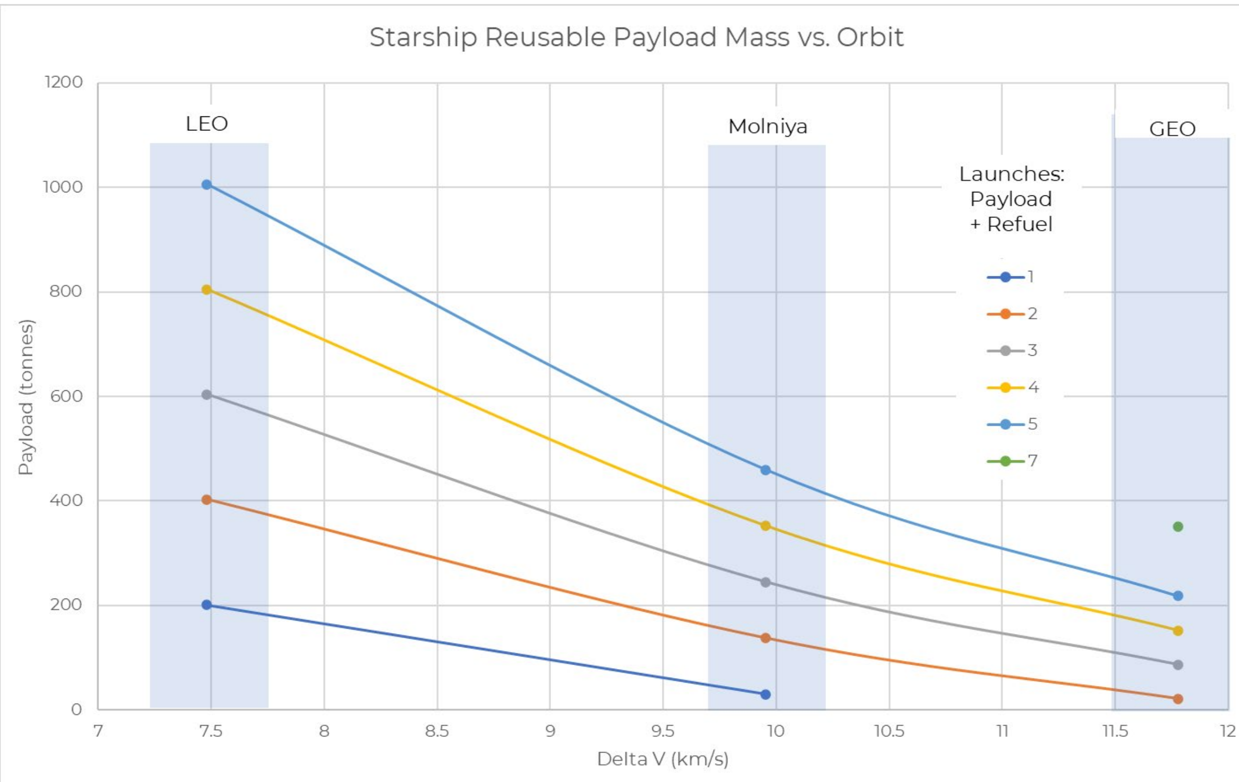

Figure 9 - Starship/Super Heavy Payload to various missions

SpaceX as a rocket developer is operational with a partially reusable family of medium and heavy lift launch vehicles called Falcon with a 3.7m diameter core and is in development of a fully-reusable 9m core super-heavy lift vehicle called Starship/Super Heavy. The specification of the Starship/Super Heavy[6] has evolved over its decade of development, with the latest specification inferred due to the upgrade in the thrust of the Raptor rocket engine to 269 tonnes thrust[7], a 17% improvement over the Raptor v2 implying an equal percentage increase in gross takeoff mass (we call that vehicle the '23 specification). Virtus Solis has developed a detailed mission design analysis code to predict the performance of launch vehicles to various missions, characterized by their required delta-V with examples shown in Figure 9. The latest Starship vehicle can deliver about 200 tonnes payload to LEO in a fully reusable configuration with sufficient propellant to deorbit and vertically land. To achieve missions with greater delta-V, SpaceX plans tanker ships with on-orbit propellant transfer, Figure 9 above shows calculated payload to higher orbits assuming 200 tonne propellant transfer per tanker in LEO. To estimate the economics of reusable launch vehicles, only a few assumptions are necessary. A

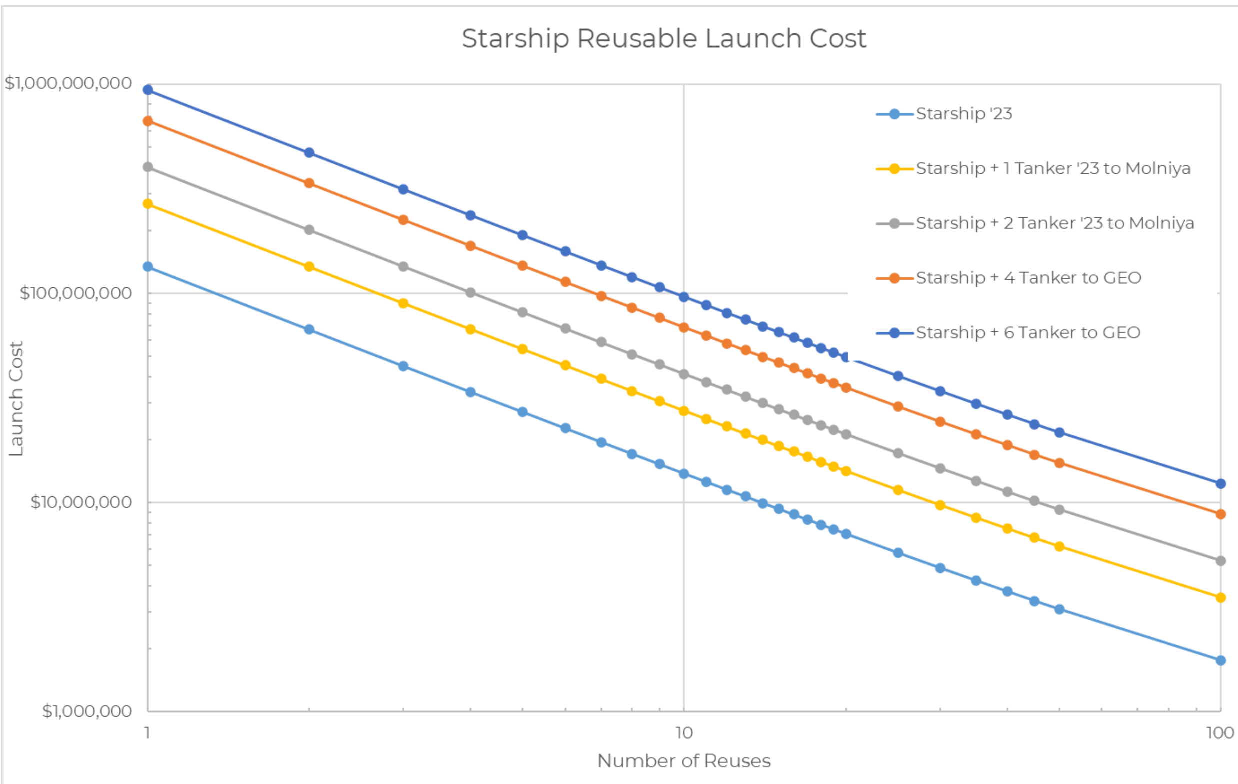

Figure 10 - Starship/Super Heavy construction and operation costs

construction fixed cost and variable cost of propellants are the only two major values, with the rocket engines being the largest portion of the cost. Our estimate is $134M for a Starship/Super Heavy first use cost, which is in-family with SpaceX estimates as well as Payload Research's analysis[8]. Figure 10 above shows a family of missions assuming a given number of new vehicles built (from 1 to 7), and then reused with the only recurring cost being propellant. SpaceX does incur some refurbishment costs every flight, but we estimate that to be insignificant as the Falcon series routinely exceeds 15 reuses today without full rebuild which is where we anchor as the maximum reuse for this analysis.

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[6] SpaceX Starship Users Guide https://www.spacex.com/media/starship_users_guide_v1.pdf
[7] SpaceX All-Hands Meeting Jan. 11, 2024
[8] Payload Research Jan. 16, 2024 https://payloadspace.com/starship-report/

Once the costs are known, the specific launch cost in $/kg can be calculated as shown in Figure 11 below. Notable is that even with no reuse, the estimated launch cost is $665/kg to LEO. Furthermore, assuming 15 reuses the cost drops to $46/kg to LEO. Higher orbits are more expensive but launch to a MEO orbit such as Molniya is only $136/kg with one propellant tanker and GEO missions get as low as $186/kg with six tankers again assuming 15 reuses for all vehicles. In fact at 100 reuses, missions to LEO are $9/kg, Molniya is $26/kg and GEO is $35/kg. These vehicles are expected to have payload handling apertures like the Rocket Cargo program[9].

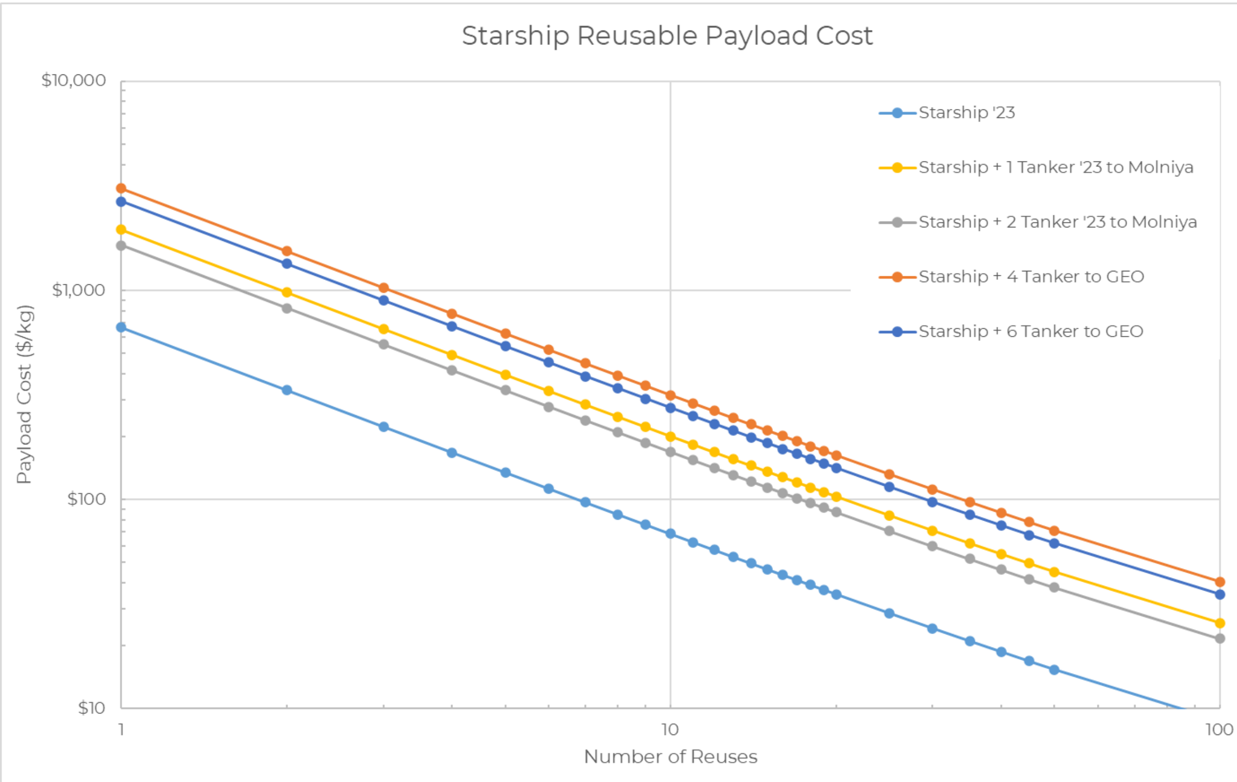

Figure 11 - Starship/Super Heavy specific payload cost in $/kg to various missions

APPENDIX II - LAUNCH COST AND LAUNCH RATE TRENDS

Two of the long-standing challenges with space based solar power have been the cost of launch and the annual launch capacity. Recent trends provide strong evidence that projected launch costs and launch capabilities will be available for cost effective and timely launch of a space based solar power satellite. Reusable launchers were the key enabling technology. They change the economics of satellite launch so that, today, the development and manufacturing costs of reusable rockets are amortized over dozens of launches. Furthermore, the refurbishment times for launchers are shrinking with the increased number of launches.

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[9] https://www.c4isrnet.com/battlefield-tech/space/2023/12/04/will-rocket-cargo-work-data-collected-in-2024-may-hold-the-answer/

The first trend is the increase in launch mass. Plotting the launched mass from 1957 through 2023 shows a distinct change in total annual mass launched. The total mass launched for 2023 is about 3 times the annual mass annually launched at the peak of the Apollo program in 1974. Figure 12 shows the break from the trend that happened in 2020. The annual increase in launch was more than 50% for the past 2 years. This strongly suggested that launch capacity will be sufficient to launch a space based solar power satellite within the next decade using a small fraction of available launch capacity.

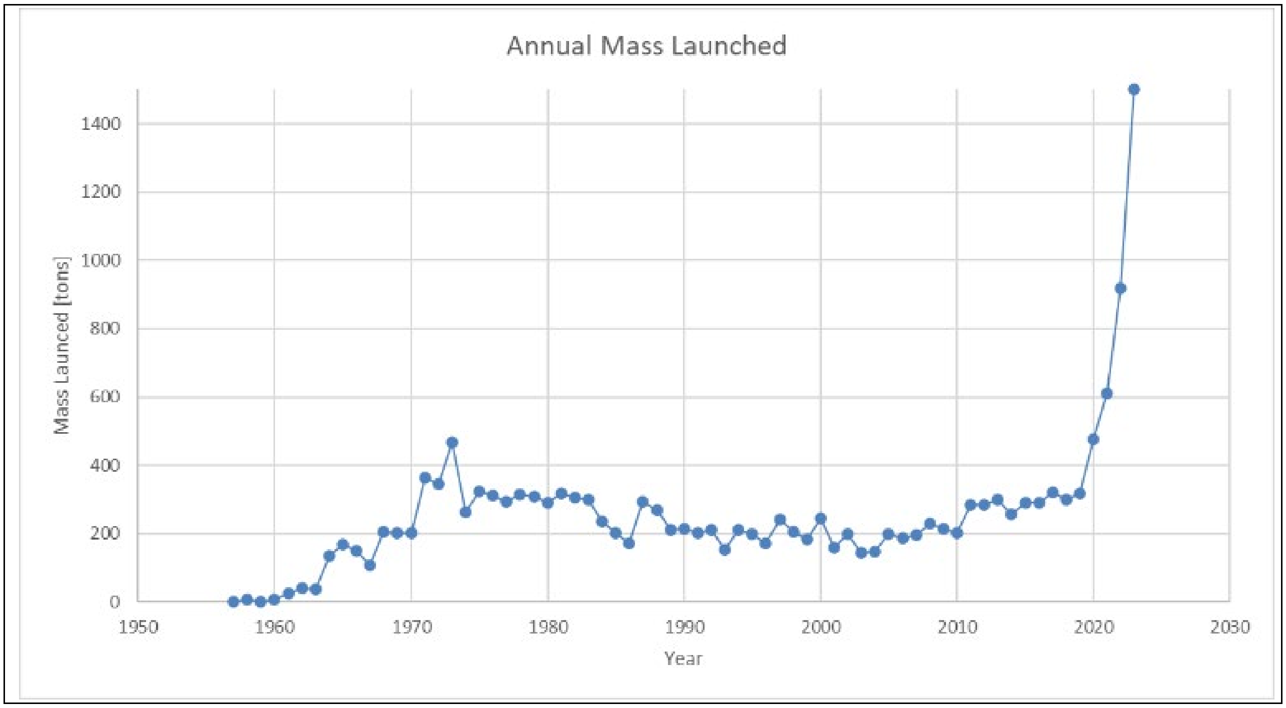

Figure 12 - Annual Launch Mass

The next trend to consider is the changes in launch costs. Wrights Law is a common methodology used to analyze changes in costs with reductions in production volumes. Wright's Law has been applied to other endeavors where repeated actions are improved over time. The key aspect of Wright Law is the presence of a learning curve that reduced costs over time as a function of cumulative production. For launch, we consider the relationship between launch costs and total cumulative launch mass. Figure 13 plots the inflation adjusted cost per kg to launch materials into orbit in 2024. At first review, the cost trend does not appear to follow Wright's law. However, if the era of launch is broken into disposable launch and reusable launch, two trend lines appear and can be fitted to learning curves. For the purposes of this analysis, the two learning curves are used as bounds on the expected progression of launch costs. An optimistic learning rate was found that reduced costs by 91% for every doubling in launch mass. A conservative learning rate that reduced costs by 36% for every doubling of launch mass. These numbers are supported by analyses and claims that the cost of a Starship launch, excluding development costs, can eventually be as low as $15/kg.

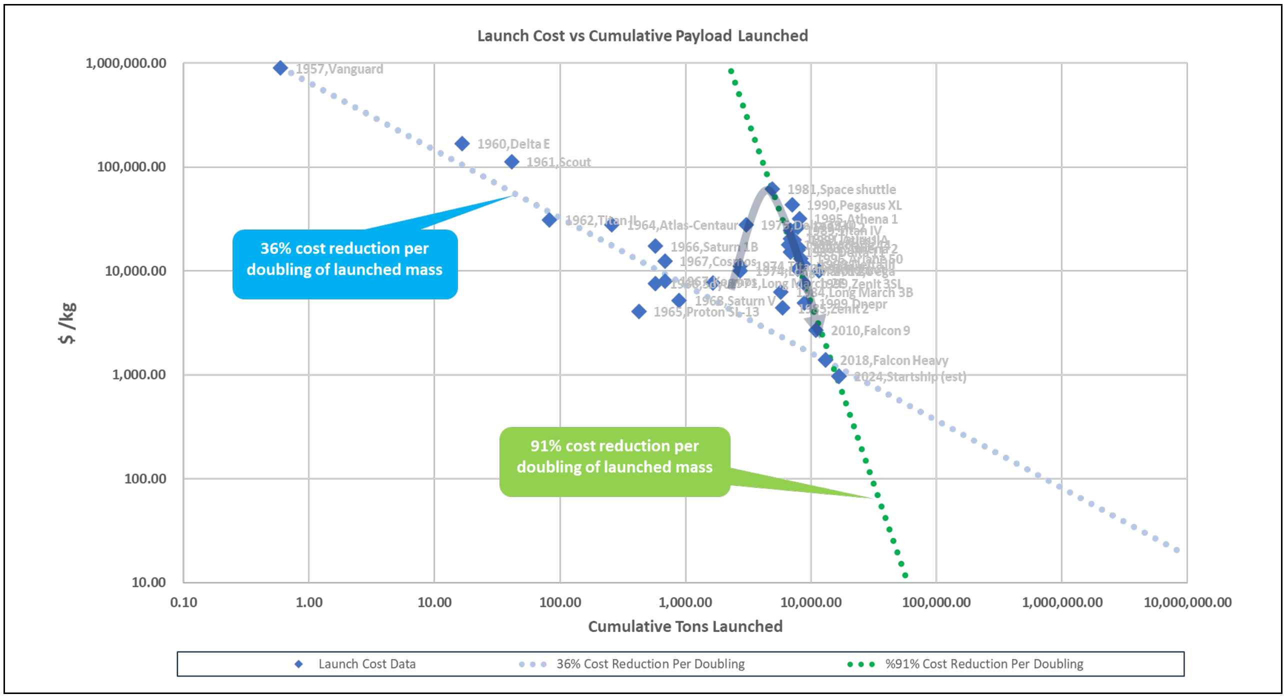

Figure 13 - Launch Costs vs Launch Mass & Trends

Total mass launched into orbit through 2023 is estimated at 17,000 tons. At 2023 launch rates, total mass launched will more than double by 2035. Using $1500/kg as a baseline in 2024, by 2035, the expected costs would be between $135/kg and $960/kg. Assuming a 15% annual growth in launch mass, by 2035 cumulative launch mass will have doubled twice yielding expected launch costs between $12.15/kg and $614/kg. The trends support launch costs in the $500/kg range within a decade.

These reductions in costs are primarily driven by the introduction of reusable launch vehicles. Reusability offers several engineering approaches to decrease launch costs. Increasing the number of reuses amortizes development and manufacturing costs over more vehicles. Improving engine and frame durability decreases refurbishment costs and increases the number of reuses. Decreasing the refurbishment time decreases financing costs. Finally, economies of scale provide other opportunities for cost reduction through things like automation and tooling.

Another issue is annual launch capacity. Again, reusability changes the total lifetime lift capability and annual lift capability. Two indicators of launch capability growth are an increased launch pace and a decrease in refurbishment of individual launchers. Figure 14 shows the decrease in time between launches that SpaceX has achieved since the first Falcon launch in 2010. After the first 20 launches, SpaceX has decreased launch time by about 1% with each launch. Furthermore, Figure 15 shows the progressive decrease in time between individual booster reuse. That data indicates that SpaceX can refurbish and relaunch within 50 days with the most recent boosters. These trends indicate that over the next decade, SpaceX and other launch providers should be able to sustain a high pace of operations. This will help decrease costs and ensure there is sufficient capability available to support large cargo lift into orbit like that required for space based solar power satellites.

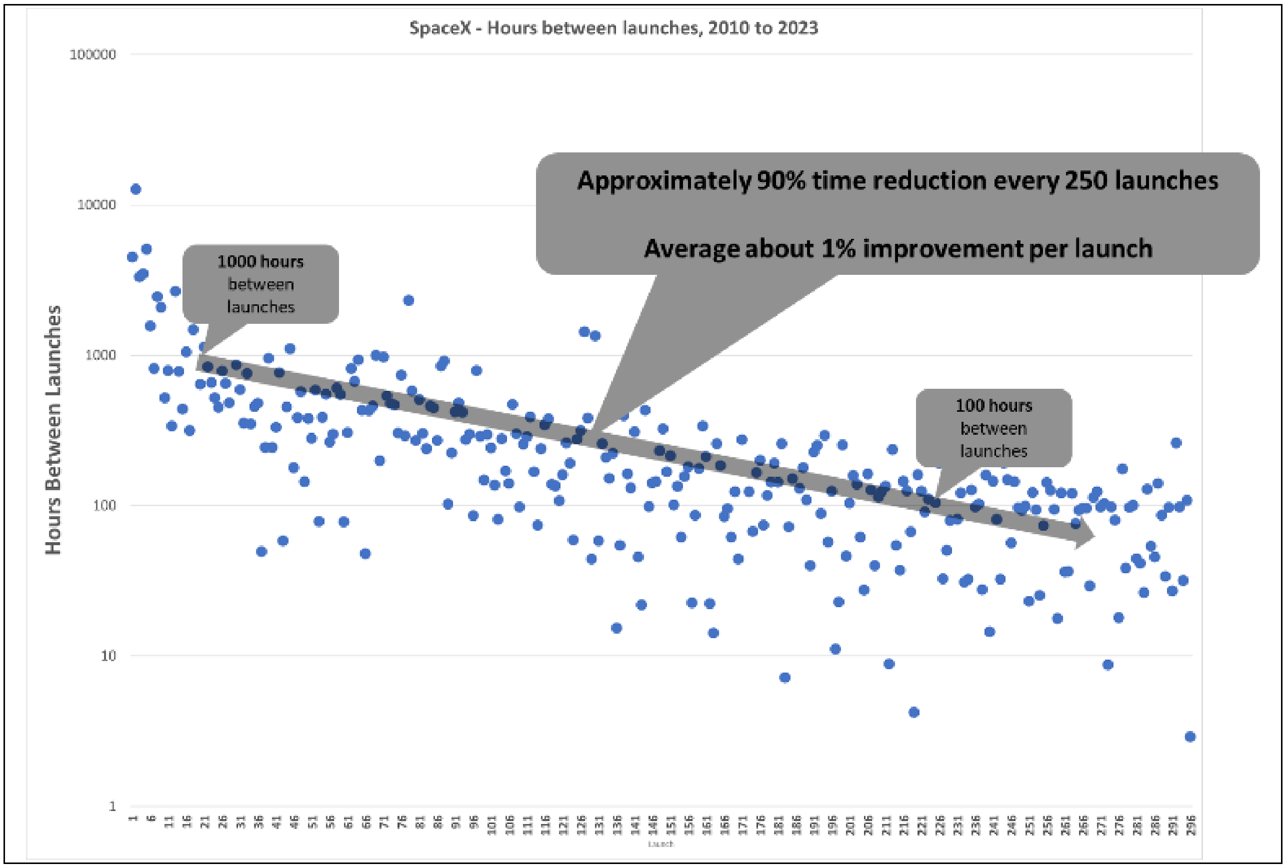

Figure 14 - SpaceX Average Time Between Launches

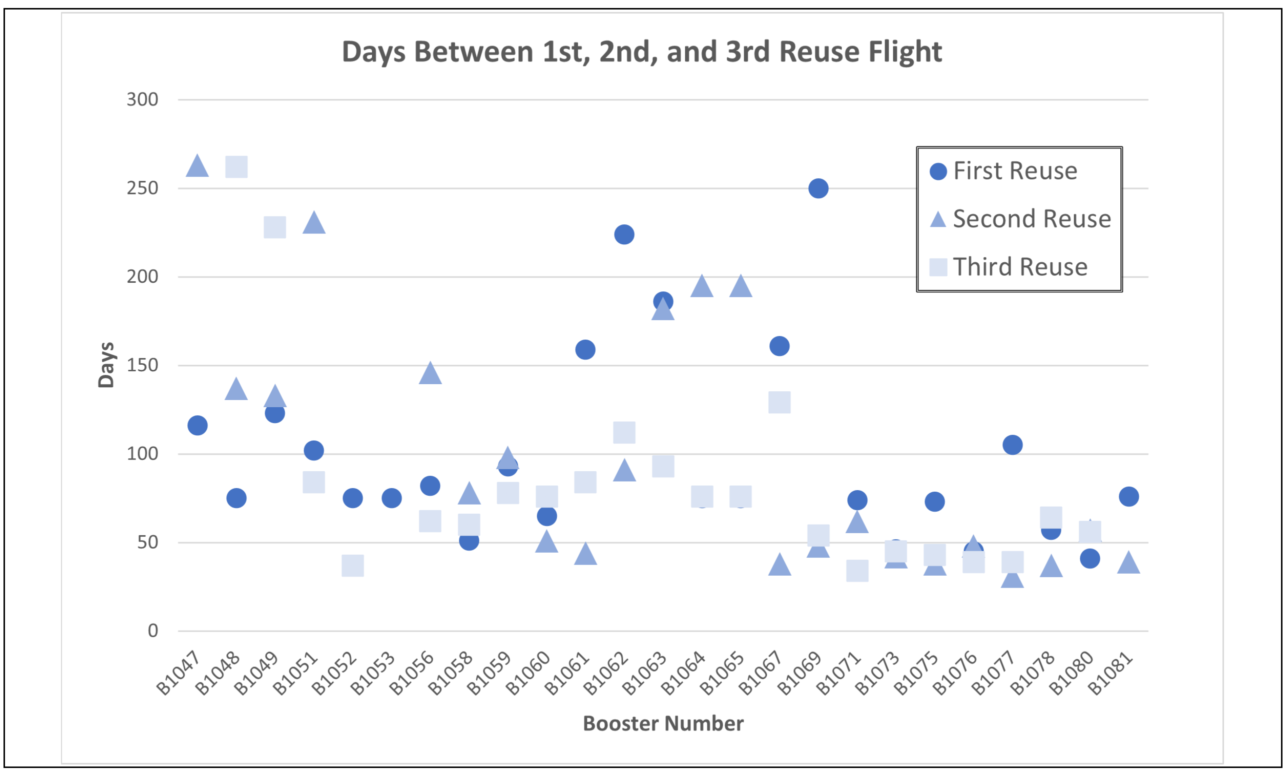

Figure 15 - SpaceX Days between Individual Booster Reuse Launches

Finally, a critical trend in the design of space based solar power is a reduction in the minimum mass required to build a commercially viable satellite. Two trends have lowered the minimum launch mass.

The first is a reduction in the mass required to generate 1kW of beamed power. This is a function of the architecture of the satellite, the conversion efficiency of the solar cells, electronics efficiency, and structural mass. In recent years, the proposed power density has increased significantly. This reflects improvements in solar cell efficiency, structural materials, and electronics. Figure 16 shows the trends in concept specific power density since the first proposed system in the 1960's.

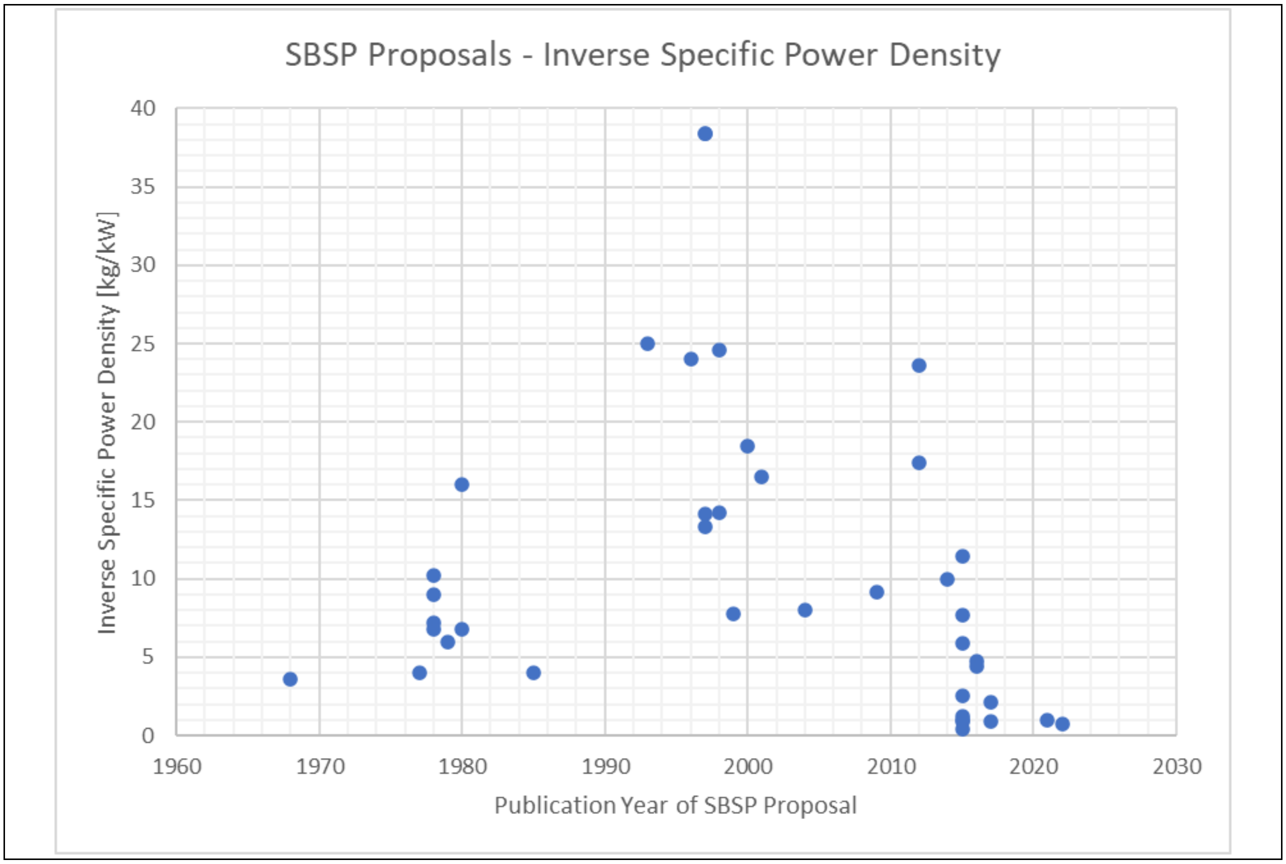

Figure 16 - SBSP Specific Power vs Year of Proposal Publication

The other trend is the minimum mass to make a commercially viable space based solar power satellite. The trends in proposals for minimum viable mass have also been decreasing as more innovative ways are devised to collect solar energy, convert it, and create an aperture large enough to efficiently beam the power to Earth. Figure 17 shows how this trend has changed since the first proposals.

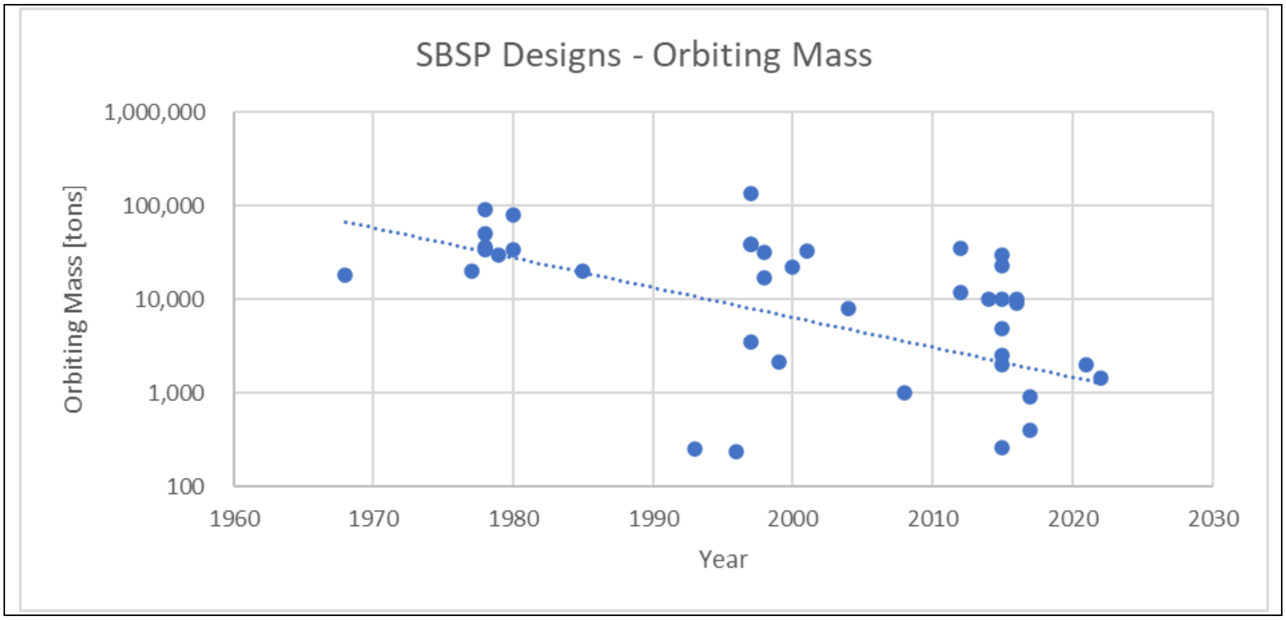

Figure 17 - Minimum Viable Mass for Published SBSP Designs

Data sets used for these analyses can be made available upon request to info@virtussolis.space .