Space Based Solar Power as a Contributor to Net Zero

Phase 2: Economic Feasibility - Annex B: Input Data Sources

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ANNEX B

This Annex describes the input data used in the LCOE model described in Annex A. Table B1 describes the information source and data derivation for each model parameter. Table B2 contains the data values for each model parameter. All cost data are converted into Pounds using an exchange rate from their year of origin [4] and then expressed in 2018 values using gross domestic product (GDP) deflators [3]. The deflation and conversion rates used are presented in Table B3.

Parameter	Type	Lower Bound / Standard Deviation	Max Likelihood / Mean / Constant Value	Upper Bound
OPEX Optimism Bias (%)	Constant		0	
Ground Station Optimism Bias (%)	Constant		0	
Satellite Optimism Bias (%)	Constant		0	
Spacelift Optimism Bias (%)	Constant		0	
Orbital Assembly Optimism Bias (%)	Constant		0	
At Grid Capacity (MW)	Constant		2000	
Design Life (y)	Constant		30	
Discount Rate (Spend)	Constant		0.2	
Discount Rate (Yield)	Constant		0.2	
Construction Time (y)	Constant		2	
Solar Insolation (W/m2)	Constant		1365	
Mirror Concentration Factor	Constant		2	
RF Frequency (Hz)	Constant		2450000000	
Maximum Beam Distance (m)	Constant		38520000	
RF Intensity Limit (W/m2)	Constant		250	
Load Factor	Constant		1	
HCPV N0	Constant		40000	
WPT N0	Constant		40000	
Thruster N0	Constant		2000	
Reflector N0	Constant		2000	
CC N	Constant		20	
CC N0	Constant		200	
Orbit keeping delta V (m/s/y)	Constant		46	
Gravitational Constant (m/s2)	Constant		9.8	
Rectenna N	Constant		1000000	
Rectenna N0	Constant		4000000	

Parameter	Type	Lower Bound / Standard Deviation	Max Likelihood / Mean / Constant Value	Upper Bound
Learning Module Mass	Constant		20	
Launch Insurance Risk	Constant		0.02	
Satellite Insurance Risk, First Year	Constant		0.07	
Annual Satellite Insurance Risk, After First Year	Constant		0.02	
Insurance Profit Margin	Constant		0.1	
Degradation Rate	Uniform	0		0.0025
O&M Factor	Triangle	0.008	0.019	0.047
Connection & Use Cost (£/MW/y)	Uniform	500		1600
Infrastructure Cost (£/MW)	Uniform	3500		15000
Pre-Development Cost (£/MW)	Uniform	40000		200000
RF to DC Efficiency	Uniform	0.82		0.88
DC to AC Efficiency	Uniform	0.95		0.985
AC to Grid Efficiency	Uniform	0.999		1
Transmission Efficiency	Uniform	0.83		0.84
WPT Efficiency	Triangle	0.78	0.85	0.87
Housekeeping Efficiency	Uniform	0.95		0.97
HCPV Efficiency	Uniform	0.33		0.42
Reflector Efficiency	Uniform	0.94		0.945
HCPV Mass Per Area (kg/m^2)	Triangle	0.27	0.34	0.4
Learning Exponent	Triangle	-0.73	-0.58	-0.24
HCPV Cost per Unit Area (£/m2)	Triangle	90	100	230
Reflector Mass per Unit Area (kg/m^2)	Triangle	0.0282	0.0367	0.0373
Reflector Cost per Unit Mass (£/kg)	Uniform	228		245
WPT Mass per Unit Area (kg/m^2)	Uniform	0.12		0.15
WPT Cost per Unit Mass (£/kg)	Uniform	1000		2600
Number of Thruster Units	Normal	60	200	
Thruster Cost per Unit (£)	Uniform	4336151		6267948
Thruster Mass per Unit (kg)	Uniform	8.5		13
Communications & Control Systems Cost per Unit Mass (£/kg)	Triangle	80000	86000	111000
Communications & Control Systems Mass (kg)	Uniform	4000		15000
Structure Cost per Unit Mass (£/kg)	Normal	30	148	
Structural Mass Ratio	Normal	0.02	0.1	

Parameter	Type	Lower Bound / Standard Deviation	Max Likelihood / Mean / Constant Value	Upper Bound
Thruster Specific Impulse (s)	Uniform	2000		2500
Land Cost per Unit Area (£/m^2)	Triangle	1.7	2.6	2.7
Rectenna Cost per Unit Area (£/m^2)	Uniform	5		8
Power Control & Mission Control Facility Cost (£)	Normal	22905617	114528083	
Electrical Balance of Plant Cost (£/MW)	Uniform	50000		180000
Spacelift Cost per Unit Mass (£/kg)	Log-uniform	358		2410
Orbital Module Mass (kg)	Uniform	20		100
Assembly Robot Cost per Unit Mass (£/kg)	Uniform	60000		500000
Mass per Assembly Robot (kg)	Triangle	10	50	100
Days of Assembly per Module (d)	Uniform	0.05		0.2
Decommissioning Delta V (m/s)	Uniform	11		600

Table B1: Cost Model Input Data Values

Parameter	Information Source and Data Derivation
Optimism Bias (%)	The application of optimism bias is discussed in section 2 of the main report.
At Grid Capacity (MW)	SBSP systems are possible at a range of scales, but to allow meaningful comparisons with other technologies the scale of the assessed system is fixed. The capacity at grid is a metric which is universal across electricity generation technologies, hence is used to define the system scale. 2GW was chosen as comparable scale to other baseload generators.
Design Life (y)	Operation life is limited by the degradation of satellite modules and the fuel needed to keep the satellite in orbit. Currently communications satellites in GEO have a life of about 15 years. Nonetheless, there is a drive to increase the life of satellites; to make better use of the materials and reduce the amount of space debris. It is judged that by 2040 there will be a business case for a useful life of 30 years. The model was used to investigate the impact of shorter and longer design life.
Discount Rate (Spend & Yield)	The discount rate used to account for the costs of capital and risks in the project is based on the projected hurdle rate required by institutional investors. This assumption was agreed after extensive discussion as suitable to provide balanced comparisons with other technologies.
Construction Time (y)	The construction time was estimated based on a reasonable estimate of spacefreight launch tempo.
Solar Insolation (W/m2)	The average standard solar radiation intensity at 1 astronomical unit from the sun (the distance from the earth to the sun).

Parameter	Information Source and Data Derivation
Mirror Concentration Factor	The degree of solar concentration provided by the mirrors on the satellite; a function of the architecture of the particular design concept being modelled.
RF Frequency (Hz)	A design parameter in the architecture of the particular design concept being modelled.
Maximum Beam Distance (m)	The distance from a satellite in geostationary orbit to a ground station located in the UK.
RF Intensity Limit (W/m2)	A design parameter in the architecture of the particular design concept being modelled. International agreement and regulation will be needed to establish safe RF Intensity Limits. In the meantime, SBSP system designers have been using 250 W/m^2, equivalent to a quarter of the noon day sun at the equator [1].
Load Factor	Load factor is a design assumption. This is slightly optimistic, as there will be some downtime for shadowing by the Earth and maintenance, but these are likely to be relatively small
HCPV N0	Modules have been classified as either general or specific when determining N_0 values. General modules are expected to have been produced outside of SBSP projects, while specific modules are expected to be unique to SBSP (Reflector, HCPV & WPT are specific, rest are general) For specific modules, $N_0 = 4N$ to account for the initial SBSP systems in the fleet, while for general modules, $N_0 = 10N$. The values of N have been rounded from estimates for SPS-ALPHA module mass [2], see Learning Module Mass
WPT N0	
Thruster N0	
Reflector N0	
CC N	
CC N0	
Orbit keeping delta V (m/s/y)	The change in velocity required to keep the satellite on station and maintain geostationary orbit [2].
Gravitational Constant (m/s2)	The standard acceleration due to gravity.
Rectenna N	There probably isn't much learning left to be done on the elements (diodes and steelwork) of the rectenna, but there may be some learning to be done on the way these are assembled together into the very large structure. Therefore the values for the rectenna are based on a rectenna module area of the order a hectare.
Rectenna N0	
Learning Module Mass	The learning module mass has been rounded from estimates for SPS-ALPHA module counts [2], based on John Mankins investigation of the optimum module size for these hyper-modular satellites [1]. This analysis has been used to establish the appropriate size of a module used for the learning factor calculations.
Launch Insurance Risk	The insurance costs for Falcon 9 rockets are currently 4% of total cost per year [3]. By the time SBSP is deployed reusable launch will be a commodity and hence launch insurance will approach costs comparable with insurance for air/sea freight. The rate for ocean freight insurance is between 0.5% and 1% of the total value for risky goods [4]. Therefore, use twice the upper bound at 2%.
Satellite Insurance Risk, First Year	Satellite insurance is derived from published risk levels in the first year (7%) and subsequent years (2%) of satellite operation [8] and an assumed 10% margin for the insurer [9].
Annual Satellite Insurance Risk, After First Year	
Insurance Profit Margin	

Parameter	Information Source and Data Derivation
Degradation Rate	Degradation factor accounts for the failure and degradation of proportion modules during the life of the satellite. The distribution assumes a range of average degradation rates from 0 to 0.25% per year;
O&M Factor	The annual operational cost of the system is the sum of two elements, ground operation and satellite operation. The costs are calculated by applying the O&M Factor to the relevant construction cost. The O&M Factor is derived from data published in the Electricity Generation Costs report [2] using fixed operations and maintenance (O&M) costs divided by 'medium' construction cost [2] for the following technologies: ▸ Biomass carbon capture and storage (CCS) (n of a kind) (Upper bound); ▸ Wave (lower bound); ▸ Geothermal combined heat and power (CHP); ▸ Hydro Large Storage; ▸ Hydro 516MW; ▸ Onshore wind; ▸ Offshore wind, and ▸ Large-scale solar (maximum likelihood). As the satellite operations predominantly consist of control and monitoring rather than maintenance, it is judged that the lower bound of this factor applies to satellite cost.
Connection & Use Cost (£/MW/y)	Connection and Use based on data published in the Electricity Generation Costs report for large scale solar [2] for the upper bound and nuclear [7] for the lower bound. These two technologies were chosen as bounds based on the determination that SBSP shares a lack of rotating mass with large scale solar and a unity load factor with nuclear.
Infrastructure Cost (£/MW)	These figures are use the range of infrastructure costs of a 3.3GW nuclear plant nuclear from the Electricity Generation Costs report [7], as the on site electrical operations for an SBSP ground station are likely to be comparable.
Pre-Development Cost (£/MW)	Pre-Development Costs are based data published in the Electricity Generation Costs report [2], using the upper and lower bounds for onshore wind [2], as this technology and SBSP sharing the need to have a large footprint.
RF to DC Efficiency	The conversion efficiency from RF to direct current (DC) within the rectenna, based on work carried out by Shinohara [9] and Brown [10]
DC to AC Efficiency	The conversion efficiency from DC to alternating current (AC), distributed according to [12] [10] [11]
AC to Grid Efficiency	The conversion efficiency from AC to the grid, distributed according to [11].
Transmission Efficiency	Transmission Efficiency accounts for the possibility that up to 2% of energy is absorbed by the atmosphere [11] and that the rectenna is sized to capture energy up to the first minimum of the Airy Disk, ie 84% of the total energy in the beam.
WPT Efficiency	Efficiency of the wireless power transmitter (WPT), using data from the IEEE International Conference on Wireless for Space and Extreme [10] and a maximum likelihood of the combination of the relevant efficiencies from proof of concept tests [13].
Housekeeping Efficiency	Housekeeping efficiency is an estimate of the power necessary to operate the satellite operation.

Parameter	Information Source and Data Derivation
HCPV Efficiency	The HCPV module efficiency is based on values from AzurSpace [14] and a survey by the National Renewable Energy Laboratory [15]. The values used capture the efficiency of the PV and losses through the primary and secondary optical elements.
Reflector Efficiency	The Reflector Efficiency is sourced from coating reflectance data for a suitable product produced by Thor Labs [16].
HCPV Mass Per Area (kg/m^2)	Mass per unit area data is based on experiments carried out by O'Neil et al [21], Although the lower value excludes some, relatively lightweight, elements, it is judged to be the most likely value as the higher value is from an early stage of development.
Learning Exponent	Learning Exponent is a coefficient expressing the effect of mass production on reducing costs. Building on the original work by Thomas Wright in 1936 (based on Boeing's production data) John Mankins has estimated that the cost/kg of SPS satellites reduce to 67% of the original cost for each doubling of production volume [19] [30], implying that: $$2^{f_{LC}} = 0.67$$ $$\therefore\ f_{LC} = -0.58$$ A range of remaining costs after a volume doubling of 60-70% is given [19] [30], leading to f_{LC} of -0.51 to -0.73. The mass-produced Starlink constellation is estimated to reduce to 85% of cost each doubling of production [44], leading to f_{LC} of -0.24.
HCPV Cost per Unit Area (£/m2)	A breakdown of HCPV cost by element [22] has been used to interpret published costs. This breakdown suggests that for a 500 times concentration HCPV module 20% of the cost is the solar cell and 15% is the secondary optical element. However, this analysis is based on terrestrial applications for HCPV, space applications will need significantly less supporting structure and hence these metrics generate conservative data. A cost range for HCPV cells and their secondary optical elements is quoted as £82.50-£112.50/m^2 [24]. Applying the cost breakdown above gives a module cost of £236-321/m^2. As these are terrestrial not space applications this is used as the upper bound cost per unit area. Horowitz et al quoted the cost of triple junction HCPV cells as $15,000/m^2 [23], which leads to a module cost of $150/m^2 accounting for the cost breakdown above and a 500 times concentration factor. This value has been used as the median cost per unit area.

Parameter	Information Source and Data Derivation
Reflector Mass per Unit Area (kg/m^2)	The reflector is expected to be a thin film supported and tensioned by a minimal frame; similar in form to a solar sail. To interpret figures for reflector mass, the planned mass breakdowns of three unmanned solar sail projects Geosail, Solo-Sail and Polar Observer, have been interpreted [17]. These breakdowns imply that: a fixed reflector of equivalent area is 23.8-46.5% of the mass of a solar satellite; a static reflector is 59-78.1% of the mass of a deployable reflector and structure is 34.5-46.6% of static reflector mass. The solar sail IKAROS [18], which was launched in 2010, has a mass of 3000kg and an area of 184m^2. Applying the breakdowns above leads to a mass per unit area of 0.39-0.76kg/m^2. The top value is an outlier from the remainder of the data, and hence is discarded, and the bottom is taken as the upper bound value. The James Webb Space Telescope, planned for launch in 2021, includes a deployable sunshield which is similar in form to solar sails and the planned reflector. The reference design mass is 200kg for five films covering 225m^2 area [18]. Accounting for the deployment mechanism using the proportions above and dividing by five to account for the multiple films gives 0.105-0.139kg/m^2. The average of these figures is taken as the most likely value. Alternatively, a mass can be derived by considering the planned film mass. Subject matter expert judgement suggests a film of 12.5μm HN polyimide and 0.1μm silver is appropriate, with a mass per unit area of 0.0188kg/m^2. Applying the ratios above gives a mass of 0.03-0.04kg/m^2. The bottom of this range is taken as the lower bound value.
Reflector Cost per Unit Mass (£/kg)	Reflector cost metrics derived from cost values for reflector pods and structural elements [19] of $400/kg and $200/kg, assuming 34.5-46.6% of the mass is structure as derived above.
WPT Mass per Unit Area (kg/m^2)	The 2000MW estimate [19] used to define the cost per unit mass are also used to define the mass per unit area. It is assumed based on the sandwich panel design of this concept that the WPT area is equal to the photovoltaic area. For baseline cases with minimal technology advances, this estimate quotes 70% WPT efficiency and 25-48% solar power generation efficiency. Therefore for 2,000MW emission the photovoltaic input power is 5,950-11,430MW, which leads to an area of 4,360,000-8,370,000m^2 assuming 1.365 x 10^{-3}MW/m^2 input power density. Dividing the stated WPT mass of 12,125,000kg [19] by these areas leads to the mass per unit area upper bound and maximum likelihood. The approach to the WPT is uncertain and other designs may result in a lower mass. SME judgement is that the mass per unit area of alternative designs could be a factor of 10 smaller than the maximum likelihood value, which forms the lower bound.
WPT Cost per Unit Mass (£/kg)	The cost per unit mass of the WPT is estimated from the cost of the materials multiplied by a manufacturing factor. These estimates are sense checked against published costs for SPS-ALPHA [19] [30], taking into account the learning factors that have been applied to these costs.
Number of Thruster Units	The number of thrusters is based on the assessment carried out for SPS-Alpha [19] giving a mean of 200 units, and applying a 20% uncertainty.
Thruster Cost per Unit (£)	The purchase cost of a thruster is based on published costs of $67,000,000 [26] and £23,000,000 [27] scaled to account for the associated research and development.

Parameter	Information Source and Data Derivation
Thruster Mass per Unit (kg)	The mass of a thruster is taken from current production models, T6 and T7 manufactured by Qinetiq [25].
Communications and Control Systems Cost per Unit Mass (£/kg)	The costs for the 'wifi router hub" and 'external comm' described above are £12,450/kg and £111,000/kg [30]. When averaged by mass, this gives a total cost per unit mass of £86,000/kg, which is taken as the maximum likelihood. A weighed average of control components (communications antenna, communication electronics, tracking, telemetry and command, attitude determination, attitude and reaction control) of £80,000/kg is taken as a lower bound [31].
Communications & Control Systems Mass (kg)	For 100MW satellites, masses of 'wifi router hub', 'external comm' and 'kernel core' are 50kg, 150kg and 15,000kg respectively [30]. The makeup of the kernel core is uncertain, hence a 4,000kg lower bound is derived with the kernel core excluded.
Structure Cost per Unit Mass (£/kg)	The cost per unit mass of the structure is based on the analysis of the cost of space hardware carried out for SPS-Alpha [19] and a applying a 20% uncertainty
Structural Mass Ratio	As the designs of the SPS are still at the concept stage an estimate has had to be made of the structural mass.
Thruster Specific Impulse (s)	The specific impulse for electric thrusters, distributed according to [29]
Land Cost per Unit Area (£/m^2)	The cost of land is based on agricultural prices per hectare throughout the UK [35].
Rectenna Cost per Unit Area (£/m^2)	Reference [30] gives justified data for rectenna costs, based on estimates of the steelwork for this size of structure and diode costs. Rectenna may be located offshore, the ratio between construction cost for onshore & offshore wind from [2] has been used to scale costs and give an upper bound.
Power Control + Mission Control Facility Cost (£)	The combination of a power control system with space mission control has few parallels and hence is challenging to predict. Fusion plants are considered a reasonable point of comparison due to the combination of controlling complex technology and power generation. The mean is derived from a fusion estimate [32] adjusted for the year of estimate and the standard deviation is a nominal 20%.
Electrical Balance of Plant Cost (£/MW)	The cost of the balance of plant is derived from the range of estimates for terrestrial solar PV based on Reference [12]. The upper bound is based on an EU assessment for solar PV [33]. The lower bound is based on work published by the US National Renewable Energy Laboratory [34].

Parameter	Information Source and Data Derivation
Spacelift Cost per Unit Mass (£/kg)	We consider two systems to explore the likely range of cost figures for the future space launch market: A fully reusable single stage to orbit Reaction Engines SABRE powered horizontal take-off and landing spaceplane. The SpaceX Starship which features fully reusable first and second stages, and with the capability of refuelling in orbit. Both systems are designed to require only modest maintenance / refurbishment between flights, rapid turnaround time, high flight rate and high utilisation. The life of the Starship is assumed to be up to 100 flights, and that of the spaceplane up to 200 flights. The SPS payloads would be launched to LEO, where a transportation infrastructure of chemical tugs would raise the payload to a medium earth orbit (MEO), just above the inner Van Allen belt, at an altitude of around 5,900km. Here the SPS would be assembled. Then the fully assembled SPS, using on-board electric propulsion, self-powered by the SPS solar arrays, would raise it into its final operational orbit. The mass ratio of propellant to payload for the chemical tugs is about 1:1, allowing for an out and return journey between LEO and MEO. Thus for each launch of an SPS payload, an additional launch would be required to ferry chemical tug propellant from Earth to LEO. Elon Musk has quoted very ambitious figures for Starship launch costs, which assumes high flight rates and a life of up to 100 flights [39] [40]. Using the chemical tug refuelling strategy, an estimated 61.3 tonnes can be delivered to GEO with 2 launches. Assuming a cost per launch comparable with the current cost for SpaceX Falcon Heavy, $100M, the cost is $3,260/kg. Reaction Engines has developed estimates for the production and operation of a spaceplane. Assuming a flight rate per vehicle of 4 per week, an operating cost of £7.5M per flight with a payload of 15 tonnes to LEO, the total cost to GEO, including the cost of chemical tug refuelling flights, is £1,340 / kg. As Spacefreight becomes commoditised, as airfreight is today, the costs reduce. Reaction Engines predict [37] that as the flight rate per year increases from 1,000 to 10,000 per year the cost falls from $400/kg to $100/kg
Orbital Module Mass (kg)	John Mankins has investigated the optimum module size for these hyper-modular satellites [1], this analysis has been used to establish the range of sizes for a module.
Assembly Robot Cost per Unit Mass (£/kg)	The costs of the robots is based on the generic cost of space hardware [1].
Mass per Assembly Robot (kg)	The assembly robots will be small articulated arms that "walk" across the structure of the satellite. The mass of the robots will be of the same order of magnitude to the modules they manipulate, but on the heavier side. The mass distribution is based on the work done for SPS-Alpha [19].
Days of Assembly per Module (d)	The range of assembly time for each module is based on judgement, recognising that all the modules will have the same interface and will go together as simply as Lego bricks.
Decommissioning Delta V (m/s)	The velocity needed to move the satellite from a geostationary orbit into a stable graveyard orbit, the range of values is taken from conference papers discussion the end of life disposal of satellites [37], [38] and a relevant patent [39].

Table B1: Cost Model Input Data Sources and Derivation

Year	GDP (2021 = 100)	Currency Conversion (GBP/USD)
1990	51.57	1.7841
1991	54.99	1.7674
1992	56.72	1.7663
1993	58.26	1.5016
1994	59.04	1.5319
1995	60.48	1.5785
1996	62.97	1.5607
1997	63.65	1.6376
1998	64.25	1.6573
1999	64.84	1.6177
2000	66.04	1.5149
2001	66.70	1.4401
2002	68.11	1.4996
2003	69.64	1.6355
2004	71.42	1.8329
2005	73.21	1.8203
2006	75.24	1.8429
2007	77.18	2.0016
2008	79.41	1.8554
2009	80.72	1.5654
2010	81.95	1.5459
2011	83.63	1.6041
2012	85.01	1.5849
2013	86.62	1.5648
2014	88.21	1.6477
2015	88.72	1.5285
2016	90.62	1.3557
2017	92.33	1.2886
2018	94.30	1.3348
2019	96.06	1.2769
2020	98.03	1.2841
2021	100.00	1.3642

Table B3: GDP Deflators and Conversion Rates

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