Space Based Solar Power as a Contributor to Net Zero

Phase 2: Economic Feasibility

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EXECUTIVE SUMMARY

This report presents the findings of an independent assessment to understand the likely cost and economic contribution of space-based solar power (SBSP) as a possible future energy technology—which could make a contribution to the UK's Net Zero target. A previous phase of this project considered the engineering feasibility for three existing design concepts. That phase concluded that engineering challenges could be overcome so that the technology could be developed. This phase uses the CASSIOPeiA concept as its reference SBSP design for the cost and economic assessment presented in this report.

This phase of the study has been informed by published literature, supported by a structured stakeholder workshop with leading space-based solar power inventors and senior figures in UK industry and academia. A bespoke cost model has been constructed to determine likely cost estimate ranges for a CASSIOPeiA design. A separate economic impact model has been developed to infer the likely indirect and induced economic effects from a successful SBSP system. Further economic considerations have been made through scenario analysis and by drawing on published information.

Findings

This study estimates that SBSP could deliver a levelised cost of electricity (LCOE) between £35/MWh and £79/MWh, assuming a successful development programme. The largest component of the LCOE is attributed to the costs of placing the satellite into orbit. Therefore the programme would benefit from a vibrant space launch market.

A significant development programme is needed to deliver the working system. The study explores the impact of an 18 year development costing in the region of £7.5bn to £16.3bn. The study has identified a range of spill-over benefits from the development programme.

Public funding will be required to ensure that a first of a kind system is commercially viable to create a market for subsequent systems. The gross economic footprint of a viable first of a kind SBSP system could be in the region of £6bn in 2018 net present value terms. It is estimated that an operational first of a kind system could realise a benefit to cost ratio of 1.8:1. The majority of key sectors are expected to grow to support the increased labour demand from the programme.

Recommendations

This study has shown that SBSP appears to be feasible from an engineering perspective (phase 1) and that—subject to development processes overcoming significant technical challenges—could provide an LCOE which could make it a highly attractive proposition for the UK's energy mix by providing continuous base load power.

Detailed recommendations are made across six areas: policy & strategy, UK led research & development, energy market engagement, space transportation, international collaboration and 'no regret' research.

As a next step we recommend that an SBSP system concept study be established, to define the user and system requirements, which would help to give performance guidelines for subsequent research activities.

CONTENTS

GLOSSARY OF TERMS

AC	Alternating Current	ISS	International Space Station
BCR	Benefit to Cost Ratio	JAXA	Japan Aerospace Exploration Agency
BEIS	Department for Business, Energy and Industrial Strategy	LCOE	Levelised Cost Of Electricity
CAPEX	Capital Expenditure	LEO	Low Earth Orbit
CASSIOPeiA	Constant Aperture Solid-State Integrated Orbital Phased Array	MEV	Mission Extension Vehicle
CCS	Carbon Capture and Storage	MR-SPS	Multi-Rotary Solar Power Satellite
CDF	Cumulative Density Function	NOAK	Nth of a Kind
CHP	Combined Heat and Power	NPV	Net Present Value
CNI	Critical National Infrastructure	ONS	Office of National Statistics
DC	Direct Current	OPEX	Operational Expenditure
ELSA	End-of-Life Service by Astroscale	PDF	Probability Density Function
EM	Electromagnetic	PESTLE	Political, Economic, Social, Technological, Legal and Environmental
EMI	Electromagnetic Interference	PV	Photovoltaic
EPSRC	Engineering and Physical Sciences Research Council	RDT&E	Research, Development, Test And Evaluation
ESA	European Space Agency	RF	Radio Frequency
FOAK	First of a Kind	SABRE	Synergetic Air Breathing Rocket Engine
GDP	Gross Domestic Product	SBSP	Space Based Solar Power
GEO	Geostationary Earth Orbit (or Geosynchronous Equatorial Orbit)	SME	Subject Matter Expert
GTO	Geostationary Transfer Orbit	SPS-ALPHA	Solar Power Satellite Via Arbitrarily Large Phased Array
GW	Gigawatt	STEM	Science, Technology, Engineering And Mathematics
HCPV	High Concentration solar Photovoltaic	TOTEX	Total Expenditure
IAF	International Astronautical Federation	TRL	Technology Readiness Levels
IOM	Input Output Model	UKRI	UK Research and Innovation
IP	Intellectual Property	UKSA	UK Space Agency
IRR	Internal Rate of Return	WPT	Wireless Power Transmission

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ECL

MANKINS SPACE TECHNOLOGY

mtc Manufacturing Technology Centre

REACTION ENGINES

ThalesAlenia a Thales / Leonardo company Space

University of Strathclyde Engineering

1. INTRODUCTION

The Department for Business Energy and Industrial Strategy (BEIS) commissioned Frazer-Nash Consultancy (Frazer-Nash), in partnership with Oxford Economics, to study the engineering feasibility, costs and economic benefits of space-based solar power (SBSP), as a possible future energy technology which could help to de-risk the UK's pathway to Net Zero. This report presents the findings of Phase 2 which considers the likely cost and further economic considerations. Phase 1 reported on the technical feasibility and development timescales.

1.1 CONTEXT

The technical and societal challenges of Net Zero are recognised, and new energy technologies are being explored. The need for base load energy is important to help ensure grid stability with a high percentage of intermittent renewable technologies in the energy mix. Space-based solar power is a developing technology with the potential to generate base load energy, and it has not hitherto been considered by the UK. Recent advances in system concepts, maturing technology, and a dramatic fall in the cost of space launch have made SBSP a more viable concept, both technically and commercially.

1.2 PHASE 1 FINDINGS

Phase 1 concluded that:

- The engineering challenges could be overcome and SBSP could be deployed operationally within the 2050 timeframe.
- SBSP could work as part of the future Net Zero energy system scenarios.
- Early technology development effort is required in a number of areas.
- The UK is well positioned across a range of technologies to play a leading role in future SBSP development.

A series of scaled technology demonstration steps were identified to establish early confidence in the system. Recommendations were made to assess the wider economic, environmental, political and societal considerations, and to undertake an initial concept design study.

1.3 STUDY SCOPE

Phase 2 estimates the development costs and through-life costs of a CASSIOPeiA[1] concept SBSP system. It then considers the economic benefits to the UK resulting from the required investment and expected spend. The study also considered the alignment of SBSP development with Government priorities, and held exploratory discussions with potential international partners.

BEIS uses levelised cost of electricity (LCOE) as a metric to allow direct comparison of different energy generation technologies. This study has developed an LCOE model of the CASSIOPeiA concept, and the approach is aligned to the BEIS methodology. Phase 1 concluded that this concept is technically viable, provides base load power, and could offer other operational benefits to the UK. In cost terms, CASSIOPeiA is probably representative of the leading base load designs. This report updates the findings on development risks, and the market and technology trends for space transportation—the dominant cost driver.

[1] CASSIOPeiA is a constant aperture solid-state integrated orbital phased array concept, designed by Cash [12].

2. METHODOLOGY

2.1 THE SUB-SYSTEMS OF INTEREST

As described in the Phase 1 Engineering Feasibility Report [1], SBSP is the concept of collecting solar energy in space and beaming it to Earth via wireless power transmission. SBSP can be configured in many different ways to deliver power for a wide variety of uses. For the purposes of this study a SBSP system is envisaged delivering power continuously into the UK grid; sized to provide 10GW of installed capacity configured as five 2GW power stations, a similar size to the UK fleet of nuclear power stations.

A SBSP system includes a solar power satellite to collect the sun, create the radio waves and beam them to earth, ground facilities to collect the radio waves and convert them electricity, and power distribution to deliver the electricity to the grid. There are also a number of support systems needed to coordinate the operations and enabling systems necessary to realise the capability, from manufacture to decommissioning. Figure 1 provides an overview of these elements of the overall system.

Whilst this study is limited to an investigation into the technical and economic aspect of SBSP it is recognised that there are wider aspects that will have to be addressed by future work. Some of these aspects are illustrated in the grey box at the bottom of Figure 1.

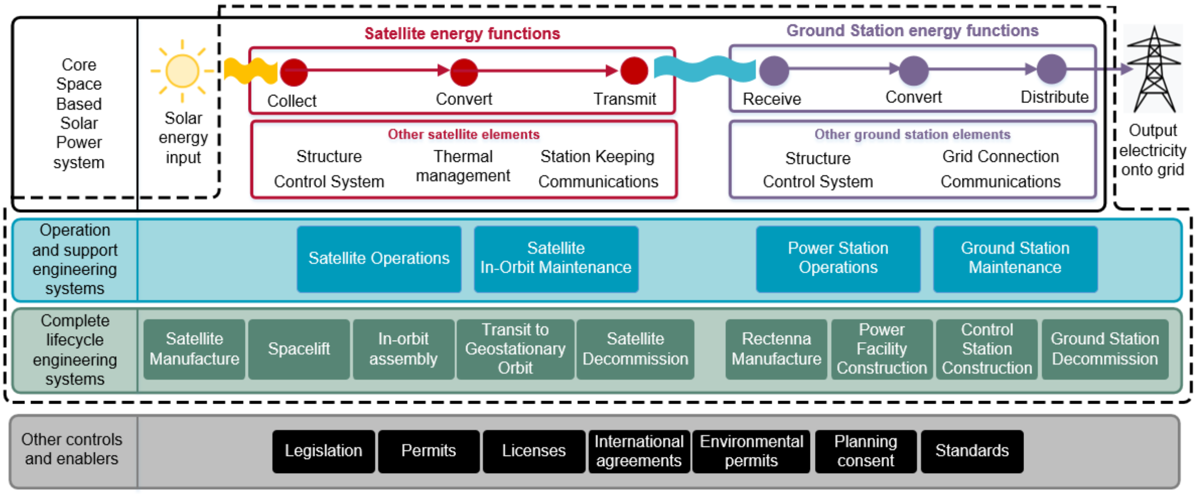


Figure 1 The sub-systems of interest

2.2 APPROACH

2.2.1 Approach to LCOE Calculation

Aspects of technology underpinning SBSP are in early stages of development, and while there are a number of proposed concepts for the system it is too early in the development cycle for the specification and final design for particular installations to have been defined. Therefore, there are several potential approaches to realising the system and considerable uncertainty in the LCOE. To account for this uncertainty, a probabilistic parametric cost model has been formulated as part of this project, which will allow:

- Determination of costs and LCOE, including confidence bounds;
- Consideration of different development scenarios and specifications for the final system;
- Understanding of the physical relationships which control costs;
- Analysis of the key contributors to uncertainty.

A key concern for the model is capturing uncertainty, both to derive confidence bounds on predicted costs and to allow different scenarios to be considered. A probabilistic model is therefore constructed, which defines the majority of parameters as distributions rather than fixed values. Particular attention is paid to the relationships between uncertain parameters and costs, such that the key drivers of cost can be determined and individual cost estimates interrogated.

All cost data in this report are expressed in 2018 values using gross domestic product (GDP) deflators [2]. Prior to deflation, costs are converted into GBP using an exchange rate from their year of origin [3]. The deflation and United States Dollar to Great British Pound conversion rates used are presented in Annex A.

The model parameters are based on the average cost of modules which could make up a ‘first of a kind’ system. The base cost information, therefore, represents the cost of a complete system if manufacture was started immediately. The information does not represent the first individual module to be manufactured, which is likely to have a significantly higher cost than subsequent modules. To model the costs of an ‘n of a kind’ system, learning factors are applied to account for the manufacturing refinement and design development which would occur during the production of multiple SBSP systems. With learning factors applied, the costs used represent the ‘n^{th} of a kind’ system cost, which is defined as the 5^{th} SBSP system of the same type constructed. With learning factors applied, the costs used represent the ‘nth of a kind’ system cost. To provide a basis for comparison the system we have modelled represents five 2GW plants, so the 'nth of a kind' in this case is the 5th system constructed. If more systems of the same type were constructed then the costs could be expected to reduce further.

The LCOE model considers a number of capital expenditure (CAPEX) and operational expenditure (OPEX) categories, of which the most complex is construction. The construction cost is based around a generic functional architecture for SBSP defined in the first phase of this project [1]. The core of this architecture is a chain of systems through which power flows from the sun to the electricity grid. These systems are modelled in three stages.

1. The ‘scale’ of each system based on physical laws, such as power conversion efficiencies or diffraction physics. The exact parameter which defines the scale varies between systems and the constraints upon them. For example, the scale of the satellite reflector is parameterised as area, and is calculated based on solar power density and the required power.
2. From the scale of each system, calculate a ‘first of a kind’ system cost and, if relevant, system mass.
3. Apply learning factors to calculate an ‘n of a kind’ system cost for inclusion in the LCOE calculation.

The LCOE model structure is shown graphically in Figure 2

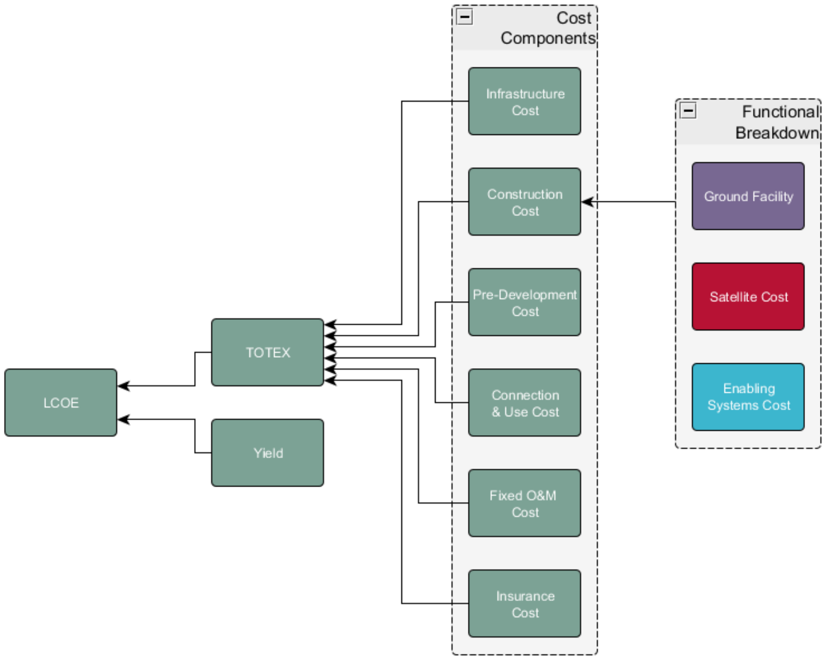


Figure 2 High level structure of LCOE model.

2.2.2 Cost components and input sources

The input data used in the LCOE model is described in detail in Annex B. Wherever possible published data has been used to generate the values for the data. In the majority of cases the published data comes from directly relevant applications. Where this is not possible analogous data or derived data has been taken from related applications. In a few cases it has been necessary to use stakeholders to estimate appropriate values. Of the 38 variable parameters used in the model, 24 use data from directly relevant applications, 9 use analogous data or derived data and 5 use estimated data. These categorisations have been used when devising the range of data values for each parameter and take an increasingly conservative view for the latter two categories.

Published data from relevant application	Analogous or derived data from related application	Estimate by Stakeholders
▸ Space-lift Cost per Unit Mass ▸ Learning Exponent ▸ HCPV Mass Per Area ▸ HCPV Efficiency ▸ Pre-Development Cost ▸ Electrical Balance of Plant Cost ▸ HCPV Cost per Unit Area ▸ WPT Efficiency ▸ RF to DC Efficiency ▸ WPT Mass per Unit Area	▸ O&M Factor ▸ WPT Cost per Unit Mass ▸ Power Control + Mission Control Facility Cost ▸ Reflector Mass per Unit Area ▸ Rectenna Cost per Unit Area ▸ Infrastructure Cost ▸ Connection & Use Cost ▸ Reflector Cost per Unit Mass ▸ AC to Grid Efficiency	▸ Degradation Rate ▸ Number of Thruster Units ▸ Structural Mass Ratio ▸ Housekeeping Efficiency ▸ Days of Assembly per Module

Published data from relevant application	Analogous or derived data from related application	Estimate by Stakeholders
▸ Communications and Control Systems Mass ▸ Land Cost per Unit Area ▸ Thruster Cost per Unit ▸ Decommissioning Delta V ▸ DC to AC Efficiency ▸ Thruster Specific Impulse ▸ Assembly Robot Cost per Unit Mass ▸ Orbital Module Mass ▸ Mass per Assembly Robot ▸ Structure Cost per Unit Mass ▸ Transmission Efficiency ▸ Communications and Control Systems Cost per Unit Mass ▸ Reflector Efficiency ▸ Thruster Mass per Unit		

Table 1 Cost Components and Input Sources – Overview

2.2.3 Approach to the economic cost and benefit analysis

The economic assessment comprised several strands of analysis which used the outputs from the LCOE model. Cost estimates for CAPEX and OPEX were used to determine development costs as outlined in section 2.2.7. In turn, these costs were adjusted to remove the effects of inflation, and discounted using HM Treasury Green Book guidance, to determine net present value (NPV) estimates in real (current) prices.

The benefits of SBSP have been estimated through a combination of modelling the economic impact to society (carried out by Oxford Economics), and drawing on secondary information to infer value for money (predominately using benefit to cost ratios for public sector research and development. Potential energy yield estimates have been calculated to enable assessment of the level of public / private funding required. Finally, a short assessment of the impact on the labour market is provided to understand the potential for the UK to provide the necessary skills and experience to deliver a SBSP system.

The approach for each element of the economic analysis is set out below.

Estimating the Economic Footprint of SBSP

This economic impact assessment comprises the employment, value-added contribution to GDP, and tax revenues supported by the required spending on the project, amongst the direct UK-based suppliers to the scheme—and through the major knock-on demand-side effects of their activity for other parts of the UK economy. All of the monetary values in this analysis are presented on a 2018 net present value basis. The effect of general price inflation has been accounted for, and a Green Book recommended real discount rate of 3.5% per annum has been applied. This means that the same monetary amount, in inflation-terms, has a lower value attached to it, the further into the future that it occurs.

More precisely, the estimates capture three ‘channels’ of impact:

- The **direct** effects relate to employment in the direct UK-based suppliers to the project—including the operators of the energy generation schemes itself once the project is up and running—and the contribution to GDP and tax revenues associated with that work.
- The **indirect** impacts relate to activity in the remainder of the UK-based business supply chain, as a result of the direct suppliers’ purchases of inputs of goods and services from third party enterprises.
- The **induced** economic contributions capture the activity supported in the wider UK economy, as a result of the wage-funded household expenditure of workers in the project’s entire supply chain.

For the purpose of this study, the SBSP ‘programme’ is split into four distinct development phases, followed by a short construction phase (CAPEX) and, then, an operational phase running for 25 years (OPEX), therefore six phases in total. Three cost scenarios are also considered, namely the high-cost (p90) assumption, central (p50) assumption, and low-cost (p10) assumption[2]. Separate economic impact assessments have been made for each of the six phases, and for each of the cost scenarios. The approach is summarised below and a detailed approach can be found in Annex C.

- Derived the output of direct UK suppliers from gross project spending – by allocating them to various industries of supplier, based on the classification of businesses found in the Annual Business Survey (ABS) published by the Office of National Statistics (ONS). The output retained in the UK was estimated based on stylised import assumptions as follows:
- Electrical and optical equipment - imports assumed to be in-line with the recent share of imports purchased by UK suppliers (two-thirds or 66%).
- Spacecraft machinery – based on current aerospace import profile which is half (50%) of the value assumed to be imported.
- Space transport services – one third (33%) assumed to be imported, in-line with existing share of air transport services currently imported.
- Construction, solar energy generation, and all other services (engineering consultancy, R&D, insurance and quantity surveying) assumed to take place entirely within the UK (zero imports).
- Split direct suppliers’ output between GDP and procurement, and estimated direct employment from direct GDP – using GDP-per-job ratios that were calculated by combining data from the latest ABS and ONS Business Register Employment Survey (BRES), forecasts to 2020 were established using the more up-to-date ONS low-level GDP data, and ONS labour market statistics.
- Split direct GDP into its components – based on average shares of each industry using the ABS.
- Estimating direct tax impacts – by calculating average wages and applying UK system for income tax, employees National Insurance contribution
- Calculate direct tax impact by adding in taxes on production (mainly business rates), Corporation tax, (charged at the proposed future main rate of 25%), taxes on products purchased (such as fuel duty), and taxes on products supplied.

[2] A p90 value indicates that 90% of the calculated estimates will be equal or less than the p90 value. The p50 is the median whilst the p10 indicates that 10% of the calculated estimates will be equal or less than the p10 estimate.

- Estimated the spending power of the direct businesses' employees – by assuming it to be equal to their take-home pay, calculated as wages net of income tax and employee NIC payments.
- Deriving indirect GDP from the direct suppliers' procurement – by categorising using the 105-industry breakdown found in the ONS UK 'input-output' table then summed up over all of the purchasing industries, to arrive at a vector for purchases by the direct suppliers to the project, from the 'second round' of UK-based suppliers. This was then combined with ratios in a specially-adapted UK input-output table, to arrive at the total value of output of the remaining UK supply chain.
- Deriving indirect employment from indirect GDP – using the GDP-to-jobs ratios and combining those productivity ratios with the indirect GDP estimates, for each industry.
- Splitting indirect GDP into its components - using the ratios from the model.
- Estimating indirect and induced tax impacts (for taxes as noted above)
- Deriving induced GDP from the direct and indirect impacts and induced employment from induced GDP.
- Summing to the total economic footprint

2.2.4 Approach to public / private sector funding

The approach to deriving the public/private sector funding for realising SBSP is based on the assumption that the first of a kind SBSP asset developed requires a hurdle rate of 20%, for it to be commercially viable. This is based on a comparison with the aerospace sector hurdle rates (between 12.5% and 14.5%) and an existing study considering global positioning satellites which concluded a hurdle rate of at least 20% to make it commercially viable [15]. The level of public funding that is required to overcome this assumed SBSP technology specific hurdle rate is then determined by setting the amount of development costs that would have to be borne by the public sector such that the private rate of return (the internal rate of return (IRR)) is equal to or exceeds 20%. If the IRR is higher than the 20% hurdle rate after increasing the share of public funding, then the public funding will be providing higher returns than necessary to secure the investment (deadweight) and crowd out other projects that could be procured (displacement).

To calculate the IRR, the p10, p50 and p90 development and operation costs are calculated separately to derive net cash flows over time. On the revenue side, a low, central and high strike price is multiplied by the p10, p50, p90 yield for the SBSP asset. The internal rate of return is based on the net cash flows over the full lifetime of the first-of-a-kind SBSP asset.

An alternative methodology could be for the UK government to set a budget constraint for the public funding that it is willing to put forward for the development of SBSP. With a given budget constraint, it is then possible to calculate what the strike price of electricity will be to allow the private IRR to reach 20%. Both of these analyses are shown in section 4.5

2.2.5 Approach to cost-benefit analysis

To estimate the economic footprint, this study categorised the expected cost of each phase of activity, and allocated them to various industries of supplier based on the classification of businesses found in the Annual Business Survey (ABS) published by the ONS [4]. Using these spend profiles, GDP estimates were made using ratios of a businesses' own contribution to GDP (technically gross value added) and its own procurement of goods and services. Assuming a constant ratio (based on a five-year average), GDP estimates of the initial spend can be estimated, using GDP-per-job ratios from the ONS Business Register Employment Survey (BRES). Then, using ONS 'input-output' tables, indirect and induced effects could be calculated.

A ratio of direct GDP to indirect and induced GDP effects can then be calculated.[3] Using these ratios, and making the reasonable assumption that GDP effects of public sector funding follow the same spending routes as those defined and estimated using input-output tables, it is possible to estimate the return on investment from different public funding contributions. The suggested public funding proportions detailed in Section 4.3 were used to determine the level of public funding and then using the GDP multipliers, an approximation of private sector return is generated.

Further benefits will be realised through the sale of electricity generated. Drawing on the data from the study's LCOE model, estimates of annual energy yield (in MW hrs) over the duration of the operational life of the first of a kind SBSP can be estimated. Taking 2018 strike price rates for comparable technologies [5] and discounting using the HM Treasury Green Book discount rates, net present value of electricity sales can be estimated. These can be compared with net present value costs for each phase of SBSP, generated using the LCOE model, also discounted with the Green Book recommended rate to derive a benefit to cost ratio.

This simple cost-benefit analysis provides an indication of the likely returns generated in terms of private sector benefits (assuming GDP contribution as a proxy for private sector returns). This is assumed to take place in 2040 and be operational for 30 years. Subsequent SBSP systems will benefit from the investments made in progressing the technology through the technology readiness levels (TRL) for the first of a kind system. In doing so, the investment risk will be significantly reduced, creating a competitive market for subsequent SBSP systems. It is likely therefore that SBSP systems beyond the first of a kind will yield far greater returns on investment than those presented in his study. An estimate of the NPV of potential energy yield for the FOAK system commissioned in 2040 is calculated using the strike price referenced in section 4.4.

2.2.6 Approach to Labour Market Assessment

The use of an input-output model (IOM) is a reasonable and credible methodology used to estimate the amount of labour market activity resulting from a direct investment into the economy. The underlying reason for this confidence is that the IOM is based on the best available information on the empirical relationships between outputs and inputs among sectors of the economy.

The IOM model has produced estimates of the direct, indirect (supply chain suppliers to direct benefitting sectors) and induced (workers spending in the economy stimulating further activity) jobs resulting from the SBSP programme.

The estimates of the direct, indirect and induced jobs (Section 4.2) can then be compared to current and forecasted jobs by industry that is expected to expand as result of a SBSP investment in the UK economy. To estimate the capacity of the labour market to provide this increase in demand for labour, data is drawn from the Business Register and Employment Survey [6] to estimate the headcounts by industry and how they have evolved over time between 2010 and 2019. The compound average annual growth rate is calculated for total employment between 2011 and 2018 to forecast what the headcount could be when the largest expansion by industry occurs. This is the presumed level per industry if the sectors continue to grow or reduce organically without the SBSP programme.

2.2.7 Approach to Development Cost Calculation

The work carried out in Phase 1 of this study identified the current level of maturity of the SBSP sub-systems, expressed as TRL, and a roadmap illustrating the development steps for a viable

[3] A detailed approach to calculating GDP contribution impacts can be found in Annex C.

pathway to a commercial SBSP system. Using the roadmap as a framework the costs necessary to complete the development phases have been estimated, as illustrated in Figure 3.

The phases of the development programme, as illustrated on the roadmap in Figure 3 are:

Phase 1 (to TRL5) 2022-2026	Ground based tests, principally investigating wireless power transmission and the application of high concentration photovoltaics. Establishing the safe level of RF intensity. Outline designs for the space power satellite (SPS) architecture.
Phase 2 (to TRL6) 2027-2031	The minimum viable size of SPS in a low earth orbit that can be put into space with a single launch. Used to confirm the viability of the selected SPS architecture and establish the communication & control protocols. Further work on wireless power transmission and atmospheric effects. Designs for autonomous assembly progressed.
Phase 3 (to TRL7) 2032-2035	Significant sized SPS in an elliptical orbit, which provides the opportunity to develop the packaging for efficient space freight, optimising the structural design of the SPS and demonstrating in-orbit autonomous assembly whilst minimising the cost of space launch. The SPS will be used to test wireless power transmission from higher altitudes and confirm the SPS control authority.
Phase 4 (to TRL8) 2036-2039	A full sized SPS in geostationary orbit, based on the first of a kind for the developed system.
Post-Development 2040 Onwards	Full sized, n^{th} of a kind SPS systems, as considered in the LCOE calculation.

The cost estimations of the development phases are built on the following structure:

- Identify the size and scale of the equipment that will be used in the prototype testing towards the end of each phase of work.
- Use the cost breakdown structure established for the LCOE calculations to estimate the cost of the hardware.
- Establish the cost of the associated research, development, test and evaluation (RDT&E) by factoring the hardware costs, based on established metrics published by Wertz in Space Mission Analysis and Design [7].
- Apportion the development costs of each sub-system over the relevant stages based on development spend distributions from the International Cost Estimating and Analysis Association [8] (see Figure 4).
- Use the LCOE cost breakdown structure to calculate the cost of the supporting systems needed for the prototype tests
- Sum the costs to provide three-point estimates, at 10%, 50% & 90% probability, for each of the phases of development.

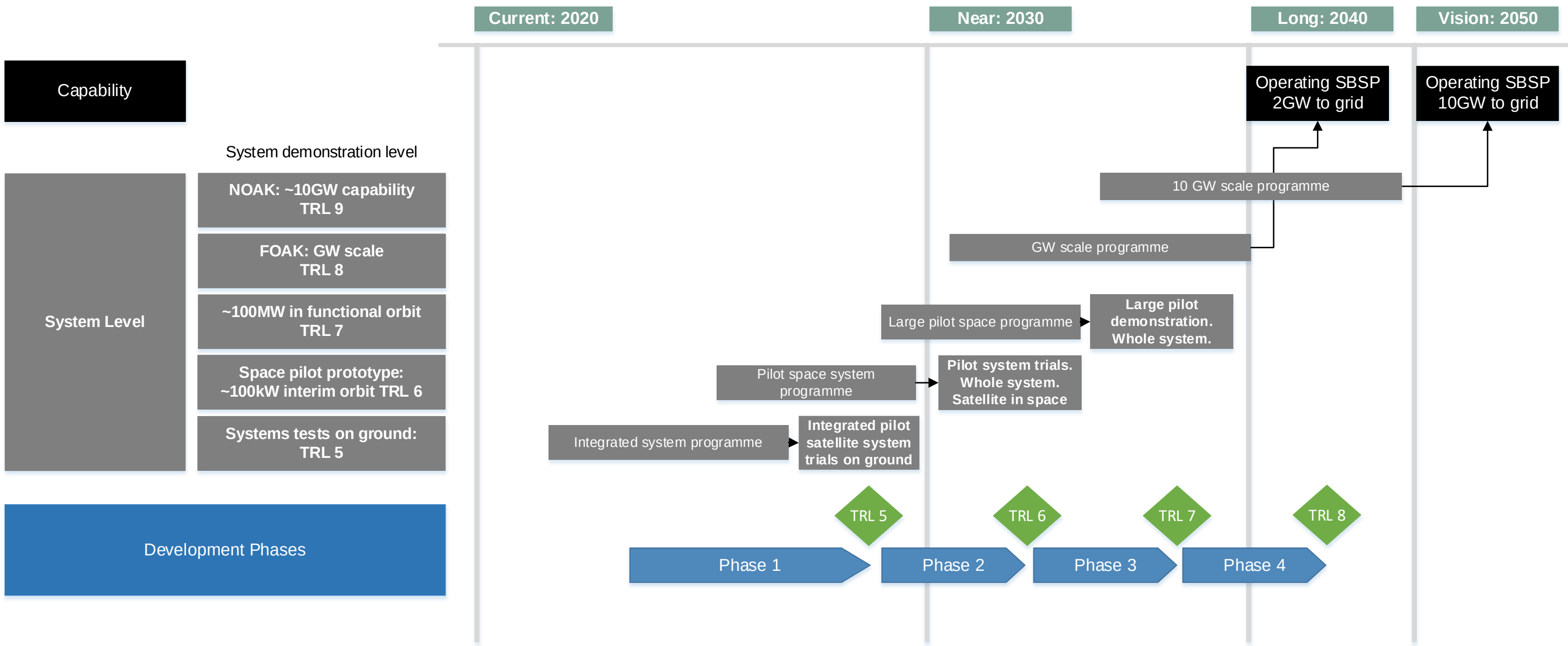
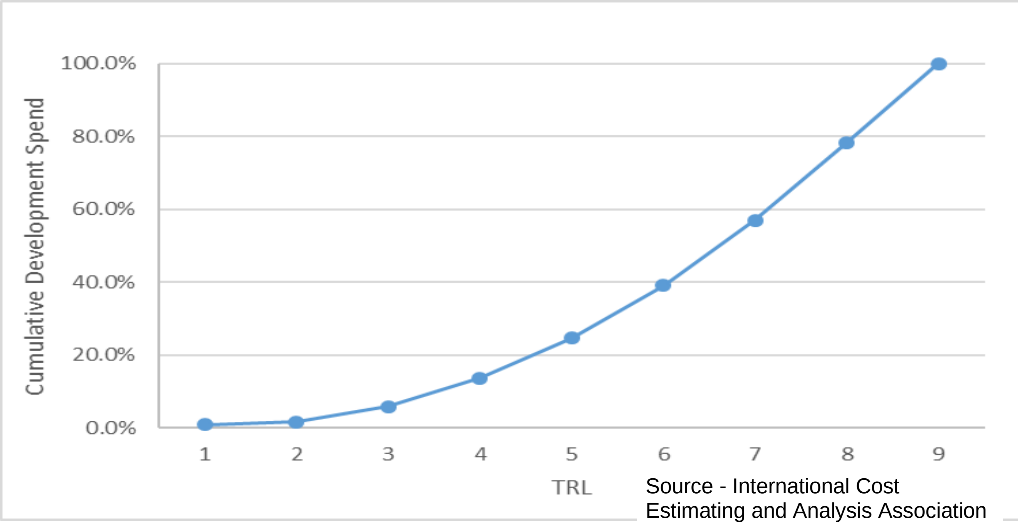


Figure 3 Development Phases overlaid on the Roadmap

Figure 4 Typical Cumulative Development Spend as a System Matures Through Each TRL



In line with the HM Treasury Green Book, optimism bias has been applied to the development costs. The appropriate project type is allocated to each cost element, as shown in Table 2. The upper bound optimism bias for the relevant project type is applied, as the project is not mature enough to justify any deviation from upper bound optimism bias.

Cost Area	Cost Element	Project Type	Optimism Bias (%)
Opex	Connection	Outsourcing	41
	Operation	Outsourcing	41
	Insurance	Outsourcing	41
Capex	Satellite	Equipment/Development	200
	Ground		
	Rectenna	Equipment/Development	200
	Land	Non-standard civil engineering	66
	Control	Equipment/Development	200
	Balance of Plant	Non-standard civil engineering	66
	Enabling		
	Launch Insurance	Outsourcing	41
	Space-lift	Outsourcing	41
	Assembly	Equipment/Development	200
	Pre-Development	Non-standard civil engineering	66
	Infrastructure	Non-standard civil engineering	66
	Engineering Team	Outsourcing	41

Table 2 Cost Elements and Optimism Bias

2.3 ASSUMPTIONS

The study assumptions and their justification are detailed in Table 3.

Assumption	Justification
The modelled system provides 2GW to the grid.	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.
The system is based on the CASSIOPeiA concept.	The different concepts for SBSP approach the challenges of the system in fundamentally different ways, which are not interchangeably compatible. This study focuses on a single concept in detail, rather than multiple concepts at a high level.
The system is based on a single 2GW, Geostationary Orbit version of the concept. The performance and mass of the satellite is within a small range around those envisaged by the designer.	Significant deviations from the designer's envisaged performance may prompt a redesign of the system, hence are excluded from the modelling.
The system will be constructed over 2 years.	Series manufacture and autonomous in-orbit assembly are key outputs of the development programme and the focus will be to drive down the construction time. Two years per satellite was chosen as a target to allow a 5 satellite system delivering 10GW into the grid to be constructed over a 10 year period. Provision is made in the model for sufficient orbital assembly capacity to support this construction period. The construction period may be constrained by the available space launch capacity. There is an expectation that there will be a vibrant global space freight industry providing spacelift as a commodity, which the UK SBSP programme can access.
The system will operate for 30 years.	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 degrades the satellite power output over its life. This de-rating is considered in the yield calculation. Due to discounting of yield in the LCOE calculation, the result is relatively insensitive to this assumption.

Assumption	Justification
The satellite is decommissioned by transfer to a graveyard orbit.	Transfer to a graveyard orbit is a current mechanism for satellite decommissioning. Alternative methods are very early in development and are heavily dependent on any regulatory regime which may evolve.
The system costed is an "nth of a kind" (NOAK) system, defined as the 5th such system constructed.	An NOAK system is considered to allow direct comparison with existing technologies which are mature and operational. First of a kind (FOAK) results have been produced for comparison.
Transfer from Low Earth Orbit to Geostationary Orbit uses either in-orbit refuelling or dedicated transfer vehicles, rather than relying on a single vehicle to transport the payload from ground to Geostationary orbit.	Multi-vehicle operational models have the potential to reduce overall launch costs, and any additional operational complexity is likely to be justified by the scale of launch required for SBSP. Neither of the proposed operating models are currently commercially available, but in-orbit refuelling is an intended capability of the Space-X Starship vehicle, which is currently in flight tests.
A 20% discount rate is used for discounting in the calculation of LCOE.	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 with the project steering group, and determined to be suitable to provide balanced comparisons with other technologies.
R&D costs for each sub-system are based around the capital costs of the first phase in which that sub-system is used.	SBSP systems are expected to be hyper-modular, composed of a large number of identical modules. Later stages of the development programme are envisaged to assemble larger numbers of modules into a system, rather than fundamentally altering the modules themselves. The development costs for each module are spread throughout the programme to allow for incremental refinement.
The HMT Green Book [9] recommended standard discount rate of 3.5% (for the first 30 years) is used for discounting costs and benefits for the economic appraisal.	To enable a fair comparison of SBSP with alternative uses of public money, all costs and benefits are discounted using the Green Book discount rate set by HM Treasury. This discounting technique enables comparison of costs and benefits that occur in different time periods on a consistent basis.
The LCOE calculations follow the methodology contained in the BEIS Electricity Generation Cost Reports	This is to allow direct comparison on a like for like basis with the LCOE for other generation technologies,

Assumption	Justification
The most recent Office for Budgetary Responsibility (OBR) Gross Domestic Product (GDP) deflators are used to inflate / deflate historic / future cash flows.	As recommended in HM Treasury's Green Book [9], the OBR forecasts are used to adjust prices from nominal to real terms, to allow a fair comparison of future cash flows.
Optimism bias is applied to the development, capital expenditure, and operational expenditure cost estimates used in the economic assessment. Green Book recommended values are used for cost items, as categorised in Table 2.	As recommended in HM Treasury's Green Book [9], optimism bias is added to all costs to account for the demonstrated tendency for estimators to underestimate costs. The published upper bound estimates are used. The LCOE calculation uses a hurdle rate to account for estimate uncertainty and does not include optimism bias as per the BEIS Electricity Generation Cost Reports.
The LCOE section is concerned with a single SBSP system as an asset, while the economic analysis section considers the entire SBSP programme as a project. Therefore, they treat risk in different ways.	In the LCOE calculation the risk manifests as the possibility the asset does not provide adequate return on investment. Therefore the hurdle rate is applied such that the risk level is accounted for in the LCOE and power generating assets with different levels of risk can be compared meaningfully. For the economic analysis, the risk manifests as the possibility of overspend on the project. This is accounted for with the application of optimism bias. Both analyses are built on the same underlying cost data for the FOAK and NOAK systems, but adapt this data differently

Table 3 Study Assumptions

2.4 METHODOLOGY LIMITATIONS

Design Immaturity

The most significant challenge in the prediction of the costs of SBSP is the low level of maturity of the concept. Several competing concepts have been proposed, and it is unclear which of these will emerge as the preferred option. A significant development programme is required before construction of a full-scale system can begin, hence the design of that system is subject to change and the performance of that system is difficult to determine.

Study Scope Limitations

The assessment conducted here has considered a single design concept and realisation of that concept. A single design specification proposed by the designer has been considered, based on the sub-system performance metrics the designer has envisaged. These metrics are supported by literature data, but this data is largely drawn from conceptual or early experimental studies, rather than productionised components or flown spacecraft. Uncertainty ranges have been included on the majority of system parameters but have been limited by what can be tolerated within the current specification.

The study scope limited the economic analysis to a gross impact assessment. This was partly due to a lack of existing information to establish a reference case, methodological limitations (see below), as well as budgetary constraints of the study.

Technology Maturity Uncertainty

The results, therefore, are contingent on a successful development programme, and no significant complications arising in the journey from concept to operations. If challenges arise which compromise sub-system performance or alter the system specification, the assessment should be reconsidered.

Economic Analysis Methodology Limitations

It is important to note that, while the economic footprint estimates capture an important dimension of the project's potential economic benefits, they do not fully encapsulate the economic case or rationale for investing in the innovative technology concerned. In particular:

- The **direct** impact reflects the value of the work undertaken by a 'first round' of suppliers to the project, and does not necessarily equate to the ultimate market value of the solar energy provided. The cost of developing, constructing and then running the operation is taken as the starting point, with these costs allowing for a 'normal' level of gross profit (before depreciation) for the suppliers and operators, as well as the cost of labour, other inputs, and taxes. But no account is taken of any additional commercial profit—or loss—that could ultimately arise for those with an equity stake in the project.
- The value of the **consumer surplus** that the final users of the technology might be able to enjoy has not been valued. Narrative regarding the potential 'spill-over' benefits is offered in Section 4.3.
- **Jobs in the supply chain** are broken down by industry, to show how they are, by and large, of a high-productivity, high-wage nature, thereby supporting the development of the UK's skills base, compared with an alternative scenario in which the same workers are employed in 'average' occupations.

3. LEVELISED COST OF ELECTRICITY

3.1 MODEL OUTPUTS – LCOE ESTIMATES

This section of the report documents the outputs from the LCOE (levelised cost of electricity) cost model.

3.1.1 Baseline Levelised Cost of Electricity

The LCOE is a basic metric used to compare the whole-life costs of electricity generation. It is the total lifetime cost of a generating plant divided by the total electricity output over the same period, typically represented in megawatt hours. The lifetime cost and electricity output are considered in net present value (NPV) terms, discounted using a hurdle rate.

The primary results of this study estimate LCOE for an nth of a kind (NOAK) system, using a 20% hurdle rate. The LCOE cost model uses probability distributions to manage the current high level of uncertainty in the system development, design and performance, given the early stage of concept design and technology maturity. The assessment indicates an LCOE range between £35/MWh (p10) and £79/MWh (p90). The p50 LCOE for an NOAK CASSIOPeiA system is estimated at £50/MWh.

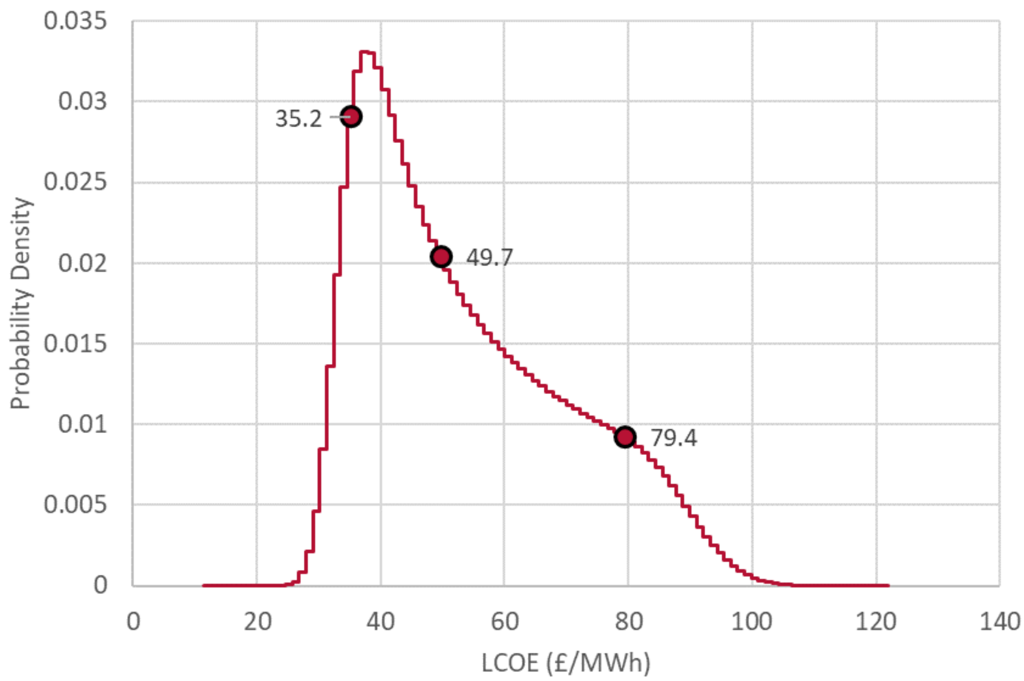


Figure 5: Probability density function (PDF) of LCOE of SBSP. Calculated using baseline assumptions: Specific realisation of CASSIOPeiA concept, NOAK, 20% hurdle rate, probabilised space lift cost, values given in 2018 prices, 30 year operational life commissioned in 2040.

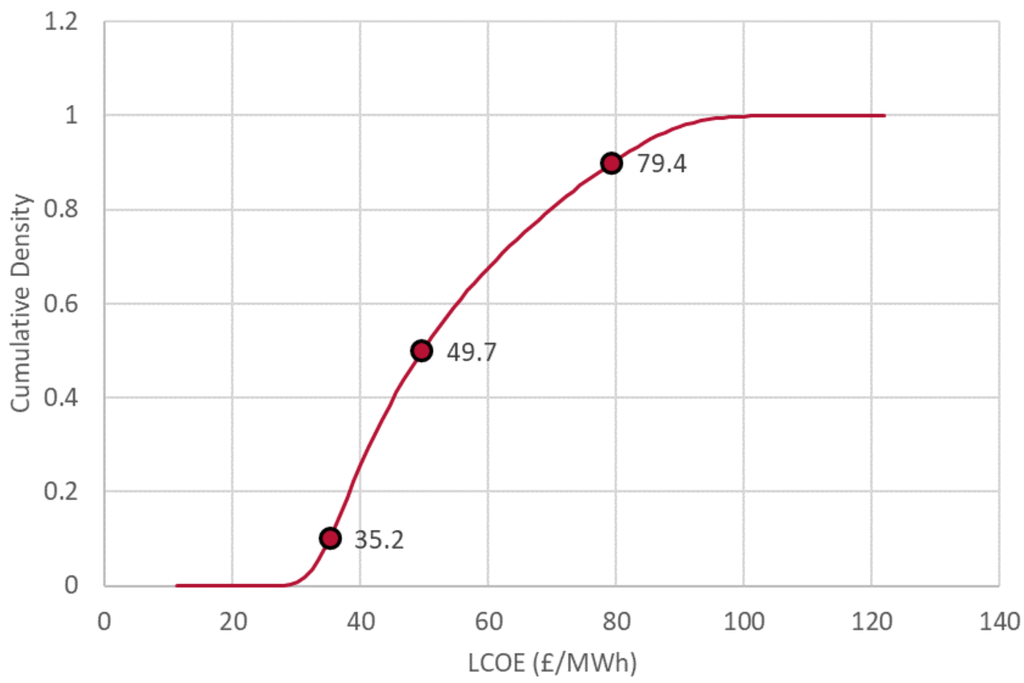


Figure 6: Cumulative density function (CDF) of LCOE of SBSP. Data points and labels 10th, 50th and 90th percentiles. Calculated using baseline assumptions: Specific realisation of CASSIOPeiA concept, NOAK, 20% hurdle rate, probabilised spacelift cost, values given in 2018 prices, 30 year operational life.

Scenario	Levelised Cost of Electricity (£/MWh)		
	p10	p50	p90
Baseline (20%)	**35.2**	**49.7**	**79.4**
Low Hurdle Rate (10%)	18.9	26.2	41.2
Reduced Hurdle Rate (15%)	26.7	37.4	59.4
High Hurdle Rate (25%)	43.6	63.2	100.9
High Spacelift Cost (£2,410/kg)	83.7	91.0	99.0
Low Spacelift Cost (£358/kg)	29.9	33.4	37.3
FOAK (first of a kind)	51.3	66.3	96.0
15 year life (20% hurdle rate)	37.3	50.9	81.0

Table 4: Calculated LCOE values for SBSP, including the results of sensitivity studies. 10th, 50th and 90th percentile values are presented. All values are in 2018 prices.

The distributions do not capture all potential designs or concepts for SBSP, instead showing the uncertainty around a single realisation of a CASSIOPeiA concept (the study reference design) based on the designer's envisaged performance. The probability density function (PDF) for this distribution is shown in Figure 5, and the cumulative density function is shown in Figure 6. The

10th, 50th and 90th percentile LCOE values are tabulated in Table 4, along with LCOE values for the other analyses considered.

A variance analysis has been conducted to understand the drivers behind the breadth of the distribution for LCOE, considering both the uncertainty in the inputs and the sensitivity of the results to each input. The analysis calculates the Sobol indices at each stage of the calculation [10] to decompose the variance into LCOE into contributions arising from the variance in each input parameter. The results of this analysis are shown in Figure 7 against a log scale, which indicate that spacelift cost per unit mass is responsible for the vast majority of the output variance. Factors affecting the performance and cost of the system account for a very small proportion of the variance, as a result of the model being based around a specific realisation of SBSP and small variations around the designer's envisaged performance metrics.

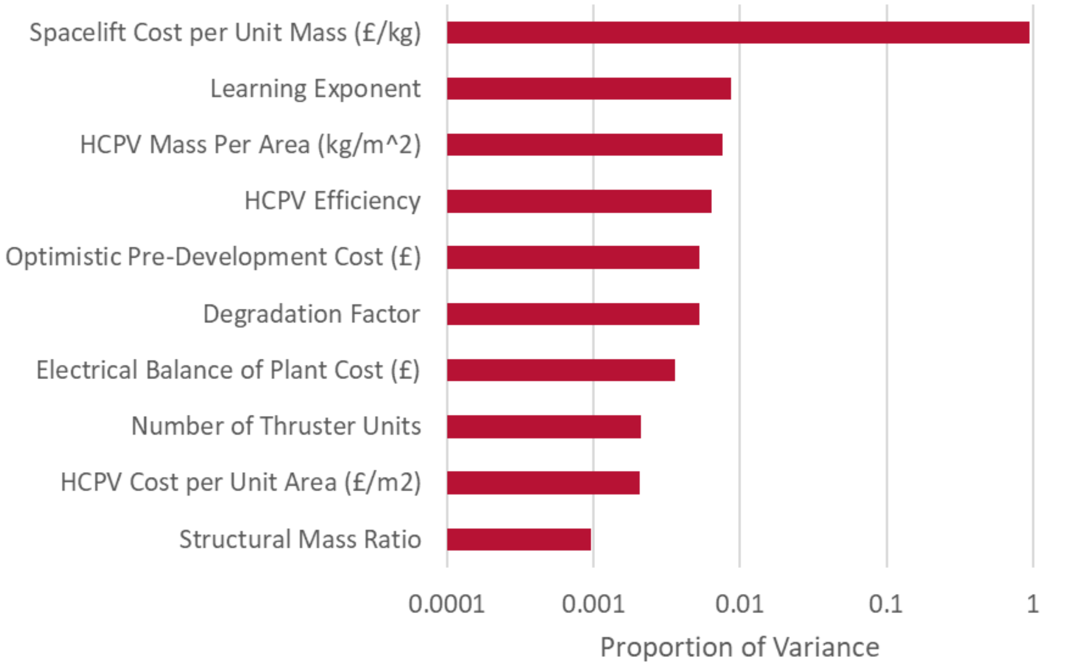


Figure 7: Results of variance analysis of LCOE of SBSP. The analysis calculates the proportion of the variance in LCOE arising from variance in each input parameter. Note that the results are presented against a log scale. Calculated using baseline assumptions: Specific realisation of CASSIOPeiA concept, NOAK, 20% hurdle rate, probabilised spacelift cost, values given in 2018 prices, 30 year operational life.

3.1.2 Sensitivity Studies

Although many of the parameters used by the model are probabilised and hence their uncertainty is captured by the distribution of LCOE, a number of potentially significant parameters are assumed as fixed values. This section presents sensitivity studies which explore the impact of changes to some of the key parameters.

It is uncertain what form the organisation which constructs or operates a SBSP system will take, or what the perceived risk of the project will be once the development programme is concluded. Therefore, LCOEs have also been calculated for a range of hurdle rates to represent possible variation in the cost of capital to the SBSP organisation. The relationship between hurdle rate and LCOE is shown in Figure 8. This shows a strong sensitivity between hurdle rate and final

LCOE, implying that correctly identifying the risks of a SBSP and cost of capital to the SBSP organisation is crucial for comparison with other energy technologies.

The period of operation of the SBSP is also uncertain, as it depends on the robustness of the satellite and the commercial case for continued operation of the ground station in the face of degrading satellite performance. The impact of altering the assumed life on the LCOE is shown in Figure 9, showing little change in LCOE even for significant alterations from the assumed lifetime of 30 years. Although the changes in LCOE with operational life are small the behaviour is complex, with the LCOE first decreasing then increasing as life is increased. The initial decrease is driven by the additional yield generated as operational life increases. The gradient of this decrease reduces at higher life as the discounting of late-life yield reduces its impact. The increase in LCOE as life increases to high values is driven by the increase in propellant requirement for station-keeping. As all propellant is assumed to be launched during construction, the costs associated with spacelift of the propellant are not discounted. An in-orbit refuelling programme could reduce the effect of the extra propellant on LCOE by pushing the cost of propellant spacelift to later in life. Overall, the lack of significant change in LCOE with operational life gives confidence in the LCOE calculation despite the assumptions made about life and refuelling.

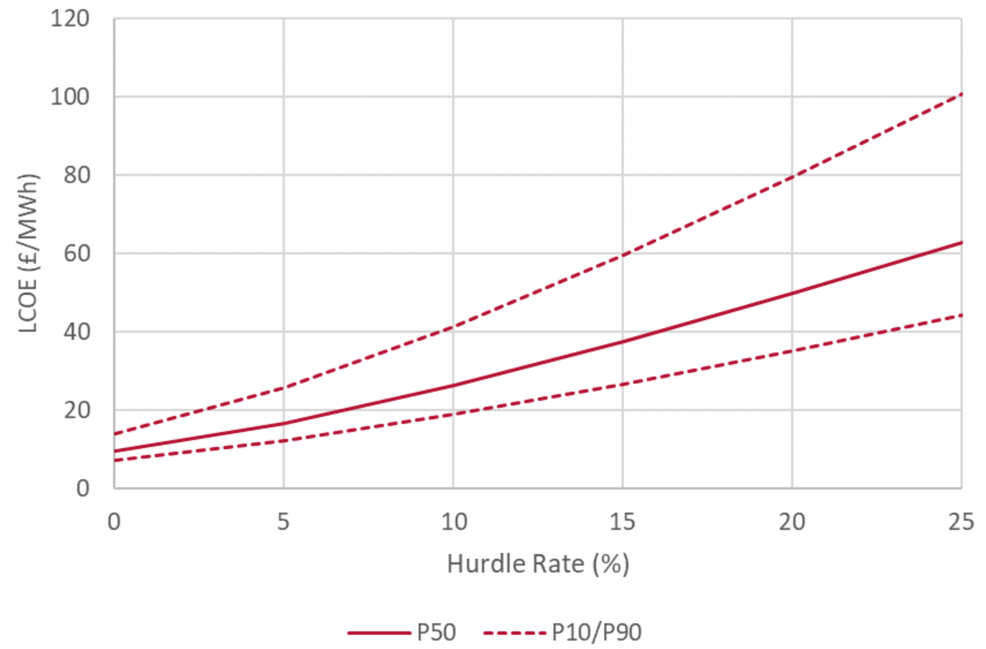


Figure 8: Relationship between hurdle rate and LCOE for SBSP, both 50th percentile and 10th/90th percentile bounds. All results use the following assumptions: Specific realisation of CASSIOPeiA concept, NOAK, probabilised spacelift cost, values given in 2018 prices, 30 year operational life.

The variance analysis concluded that the cost per unit mass of spacelift is the driver of the majority of uncertainty in this analysis of LCOE. The sensitivity of LCOE to spacelift cost per unit mass is shown in Figure 10. Horizontal lines indicate the bounds of the primary results. Consistent with the variance analysis there is a strong dependency between spacelift cost per unit mass and LCOE, and fixing the spacelift cost leads to a significant reduction in uncertainty compared to the primary results. As noted by the variance analysis, the analysis only considers limited deviations from specific design and performance metrics, leaving spacelift cost as the most significant residual uncertainty. Any work which can provide enhanced insight into the evolution of the spacelift market will significantly refine the economic analysis of SBSP.

The NOAK results presented assume the system is the 5th such system constructed, and hence efficiencies have been made in manufacturing processes reducing the LCOE. The LCOE of the FOAK or first full-scale system constructed is compared to the NOAK in Figure 11. The FOAK system has a modest increase in LCOE compared to the NOAK, and a slight reduction in uncertainty, as the effects of uncertain learning factors are removed. Note that some gains in efficiency are assumed for elements of SBSP which are common with other satellites, specifically communications, control systems and thrusters.

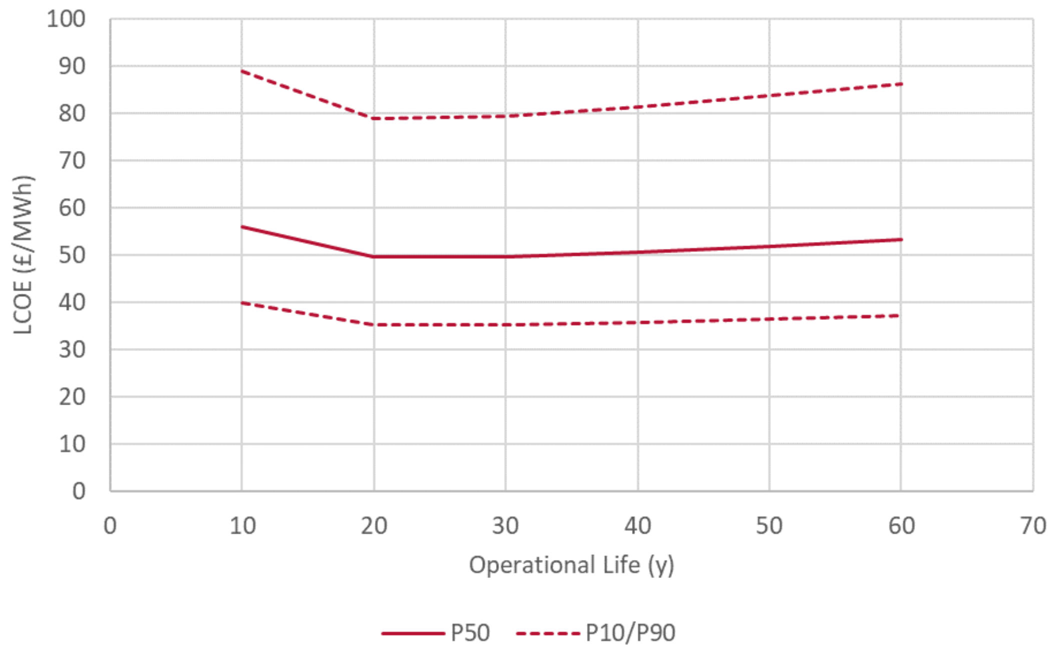


Figure 9: Relationship between operational life and LCOE for SBSP. The increase in LCOE at long lives is a result of the assumption that the satellite is not refuelled in operation, but carries all required propellant throughout life. All results use the following assumptions: Specific realisation of CASSIOPeiA concept, NOAK, 20% hurdle rate, probabilised spacelift cost, values given in 2018 prices.

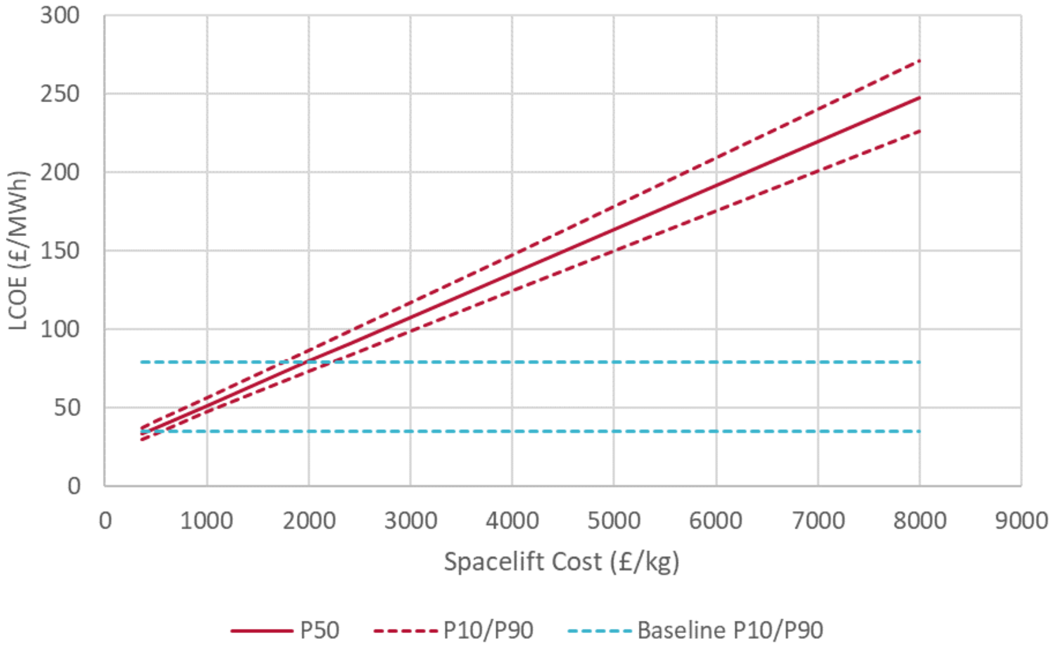


Figure 10: Relationship between spacelift cost rate (per unit mass to GEO) and LCOE for SBSP. All results use the following assumptions: Specific realisation of CASSIOPeiA concept, NOAK, 20% hurdle rate, values given in 2018 prices, 30 year operational life.

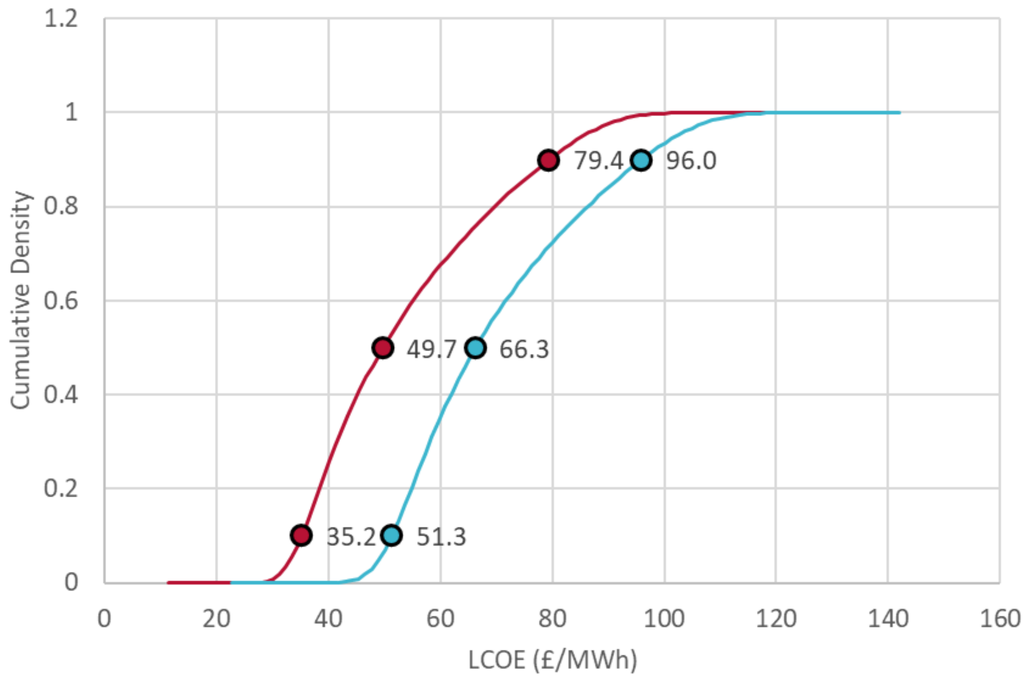


Figure 11: Cumulative density function (CDF) of LCOE of a first of a kind full-scale SBSP. Data points and labels 10th, 50th and 90th percentiles. Calculated using baseline assumptions: Specific realisation of CASSIOPeiA concept, NOAK, 20% hurdle rate, probabilised spacelift cost, values given in 2018 prices, 30 year operational life.

3.1.3 Comparison with other SBSP estimates

Several authors have studied the LCOE of SBSP and published a range of estimates. Most publications on the subject acknowledge the uncertainty in some of the key assumptions which drive the LCOE of SBSP, and hence produce a range of estimates to explore the sensitivity of the LCOE to the input assumptions. Two single-point estimates have been selected for comparison with the baseline results of this study, originating from Mankins [11] and Cash [12] These estimates are for the same scale of system in the same orbit as this study (2GW in GEO), and the Cash estimate is for the same concept and realisation. Model calculations have been performed with equivalent hurdle rates and system operational lives.

Mankins' estimate is compared to model results with an equivalent 0% hurdle rate in Figure 12. The distribution of LCOE predicted by the model falls significantly below Mankins' estimate. The main factor driving this difference is the mass of the SBSP satellite, which depends on the SBSP concept. The CASSIOPeiA concept considered by this study claims a significantly reduced satellite mass than the SPS-ALPHA concept evaluated by Mankins for an equivalent grid power output. As spacelift is a very significant contributor to the costs of SBSP, a lighter satellite results in reduced LCOE.

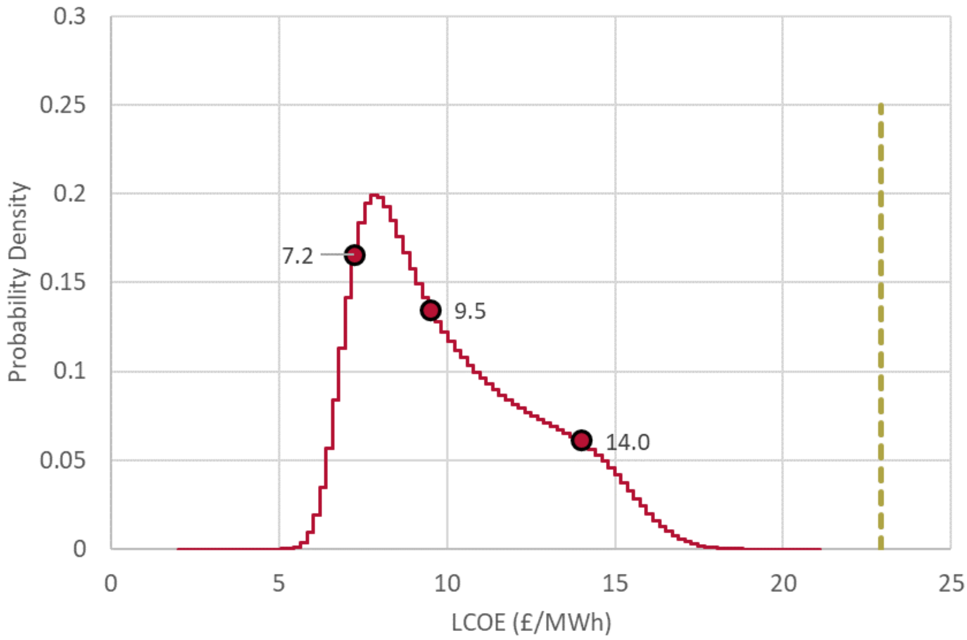


Figure 12 Probability density function (PDF) of LCOE of SBSP, comparing results of this study to previously calculated estimate. Model results use baseline assumptions, with the exception of a 0% hurdle rate. Estimate is selected from those produced by Mankins [11], adjusted to 2018 prices.

Cash's estimate is compared to model results with an equivalent 20 year operating life and 3.5% hurdle rate in Figure 13. The model results fall below Cash's estimate, despite both values considering the same concept. There are two factors contributing to this difference: the specific specification of the SBSP satellite and the cost of spacelift. Since publishing these results, Cash has refined the specifications of CASSIOPeiA systems further, and one of these more refined specifications has been modelled in this study. These refinements principally consisted of the addition of a concentration effect to the reflector, which reduced the LCOE compared to that published in 2019. These refinements have reduced the LCOE compared to that published in

2019. The cost per unit mass of spacelift assumed by Cash is the upper bound of the distribution used in this study, leading to the model LCOE results falling below Cash's estimate.

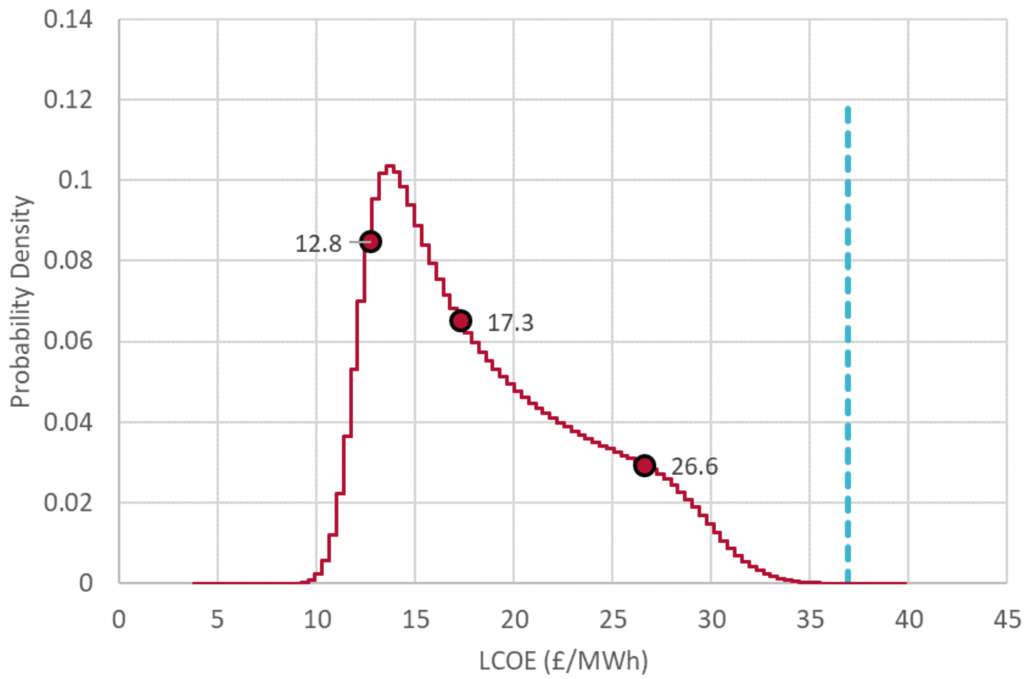


Figure 13 Probability density function (PDF) of LCOE of SBSP comparing results of this study to previously calculated estimate. Model results use baseline assumptions, with the exception of a 3.5% hurdle rate and 20 year operating life. Estimate is selected from those produced by Cash [12], adjusted to 2018 prices.

3.1.4 Comparison with other energy generation technologies

The LCOE presented in this section has been calculated to allow direct comparison with published values for other technologies [13]. For consistency with the data for SBSP the LCOE for the other generation technologies are taken from plant commissioned in 2040. A comparison of the predicted LCOE for SBSP with selected other technologies is presented in Figure 14. The plot indicates uncertainty bounds and most likely predictions, defined as the 10^{th}, 50^{th} and 90^{th} percentiles for SBSP and the "low", "med" and "high" published values for other technologies. The reference plant sizes and hurdle rates used in the calculation are included alongside the technology names.

The predictions for SBSP have a higher range than those for other technologies, due to the comparatively low level of maturity of SBSP. At the lower end, the LCOE for SBSP is comparable with LCOE values for conventional solar and wind energy. It should be noted that the costs of managing intermittent supply to the grid is not included in the published LCOE values, so the baseload supply from SBSP may be preferable to wind and conventional solar given similar LCOEs. The higher end of SBSP LCOE competes with other dispatchable or baseload technologies, such as closed cycle gas turbines with carbon capture and storage, or nuclear plants. For the comparison with nuclear, note that the SBSP presented is NOAK, and the equivalent FOAK SBSP system has slightly higher LCOE, as shown in Figure 11. This FOAK LCOE encompasses the predictions for nuclear at the upper end.

LCOE predictions for SBSP are highly sensitive to hurdle rate, as shown in Figure 8, and launch cost, as shown in Figure 10. Hurdle rate is treated as certain in the modelling, so controls the vertical position of the red bar, while launch cost is treated as uncertain, so drives the size of the red bar. The comparison to other energy technologies has been made using the baseline hurdle rate of 20% and technology specific hurdle rates for each of the comparator technologies. The 20% hurdle rate assumed as a baseline for SBSP is significantly higher than those used for the other technologies, to account for the low level of SBSP maturity and consequent risk in a SBSP project. If SBSP systems prove to be reliable and initial projects are successful, it may become justified to apply a hurdle rate similar to that applied to other technologies, in which case SBSP becomes extremely competitive.

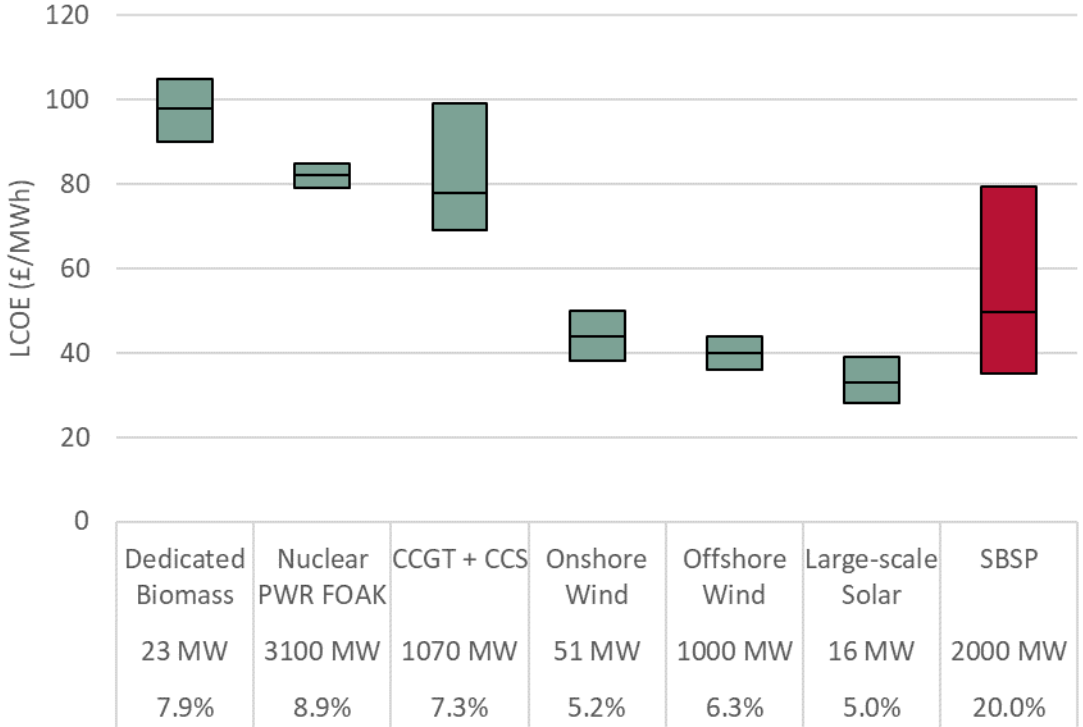


Figure 14 Comparison of SBSP LCOE predictions with those published for other technologies [13], all plant commissioning in 2040. For SBSP, the bar represents the range between the 10th and 90th percentiles and the horizontal black line represents the 50th percentile. For other technologies, the bar represents the range between the "high" and "low" values and the horizontal black line represents the "mid" value. Nominal system capacities and hurdle rates are presented alongside the technology names.

The contributions to LCOE for SBSP and selected other technologies in the 50th percentile or "mid" scenario are compared in Figure 15. Carbon costs, CO2 transport & storage costs and decommissioning & waste costs have been combined for simplicity. SBSP is characterised by a large contribution from construction cost and small contribution from operational cost. SBSP shares a large contribution from construction cost with nuclear, but has proportionally lower operating costs and no fuel costs. The concept modelled is decommissioned by transfer to a graveyard orbit using propellant included in the initial payload, so the cost of decommissioning is included in the cost of construction. Decommissioning of the ground station is assumed to have zero cost, as the cost of disassembly is assumed equal to the scrap value of the components. This assumption is consistent with the LCOE calculations for the majority of the technologies considered

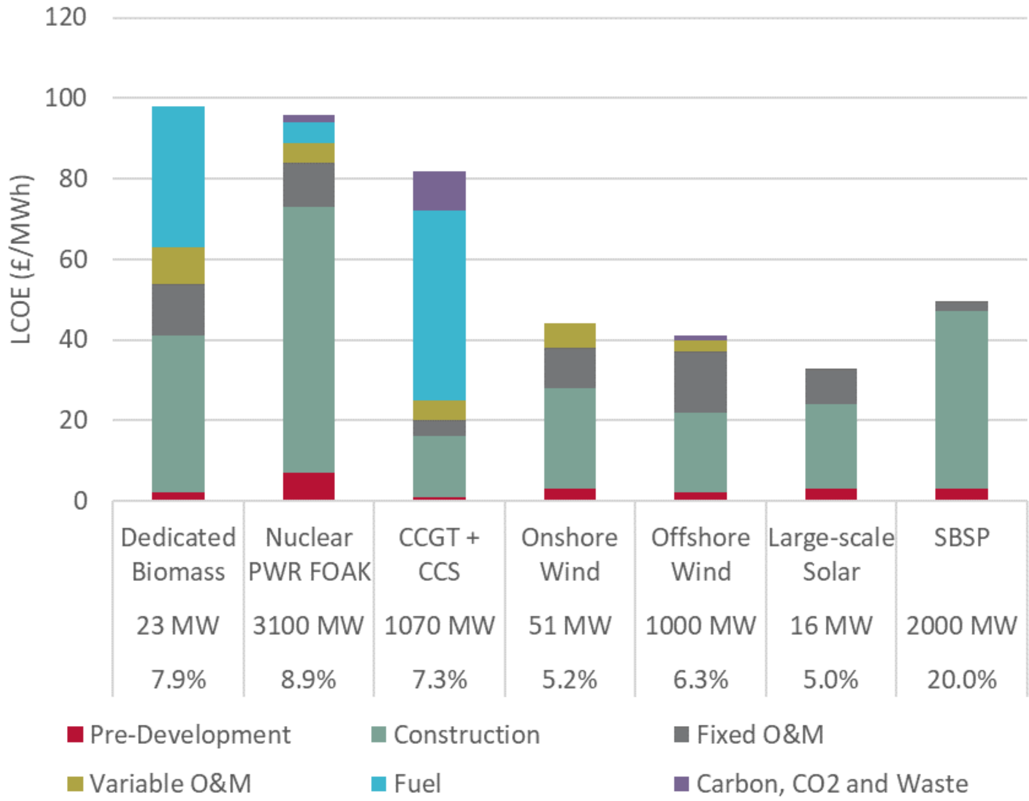


Figure 15 Comparison of 50th percentile SBSP LCOE predictions with “mid” values published for other technologies [13]. Nominal system capacities and hurdle rates are presented alongside the technology names.

4. ECONOMIC COSTS AND BENEFITS

This section details the economic assessment of SBSP programme costs and benefits. In doing so it sheds light on the potential viability of pursing an SBSP capability within the UK. It considers the costs and benefits to society of a CASSIOPeiA concept system, including return on investment and wider social and economic benefits.

4.1 SBSP COST ESTIMATES

To derive an LCOE estimate (see sections 2.2.1 and 3.1), estimates of capital expenditure (CAPEX), operating expenditure (OPEX), development costs, and energy yield of the asset have been made. This information has been used to inform an assessment of the costs and benefits of a programme culminating in a UK based SBSP system. Figure 16 shows the predicted distributions of CAPEX and OPEX for the NOAK system considered by the LCOE calculation, including 10th, 50th and 90th percentile estimates.

The breakdown of CAPEX and OPEX into components is shown in Figure 17, against a log scale. Construction is the dominant cost component, and accounts for the majority of the total expenditure (TOTEX) of the modelled SBSP system. The next two most significant components are operations & maintenance and insurance cost, which are both driven by the high cost of the satellite and ground facility.

In addition to CAPEX and OPEX for the NOAK system, the costs of each preceding stage of a development programme have been calculated as described in section 2.2.7. Table 5 shows the resulting development cost estimates by phase.

To enable a fair economic evaluation of the programme, HM Treasury guidance has been adopted. Thus, this assessment provides net present value (NPV) estimates using the Green Book recommended social value discounting rate of 3.5% (up to 30 years),[4]. The LCOE model outputs real prices (2018) which were inflated (using GDP deflators) and then discounted to derive NPV estimates in todays (2021) prices.

Optimism bias has been included to all costs for the economic assessment, in addition to application of the Green Book recommended discount rate. Each element of the costs has been mapped to the appropriate optimism bias category, as previously shown in Table 2. The resulting optimism bias adjusted distributions of CAPEX and OPEX are shown in Figure 18, alongside the unadjusted distributions.

[4] 3% for 31-75 years.

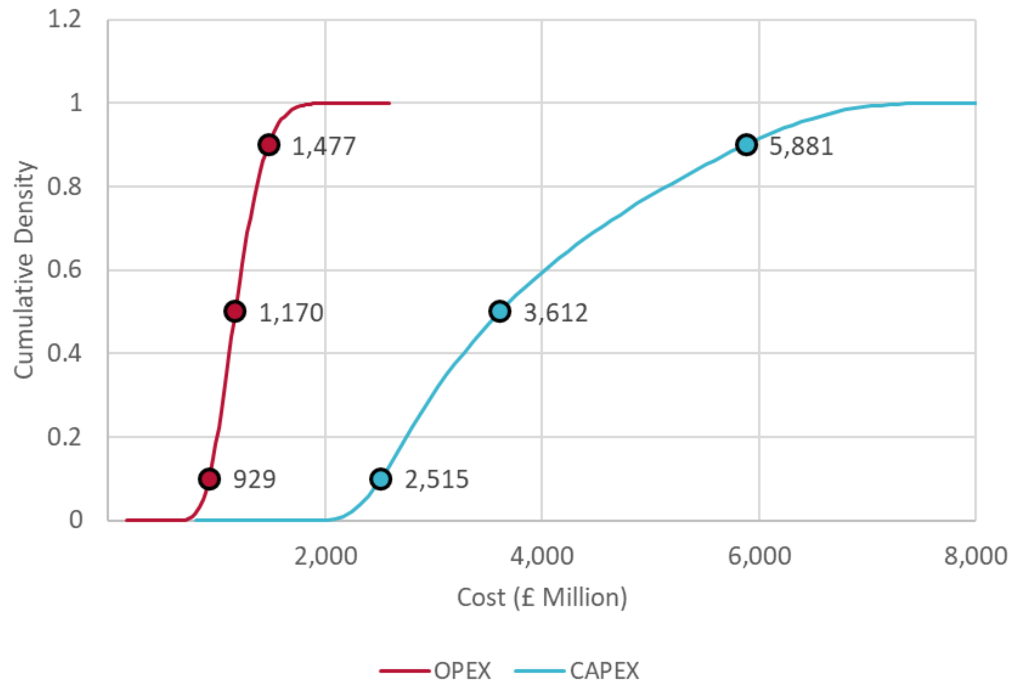


Figure 16 CAPEX and OPEX predictions for an NOAK SBSP system. Assumptions used are those from the baseline LCOE calculation. Markers indicate 10th, 50th and 90th percentiles, with their values in £ Million.

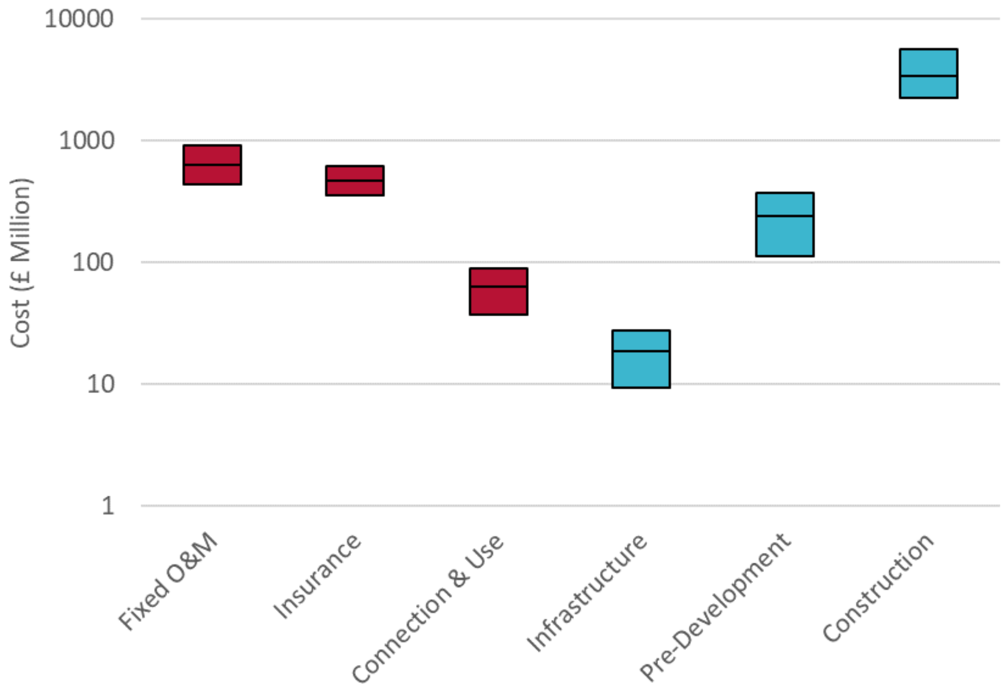


Figure 17 CAPEX and OPEX breakdown for an NOAK SBSP system, against a log scale. Assumptions used are those from the baseline LCOE calculation. Bars indicate the 10th to 90th percentile range with a horizontal black line at the 50th percentile.

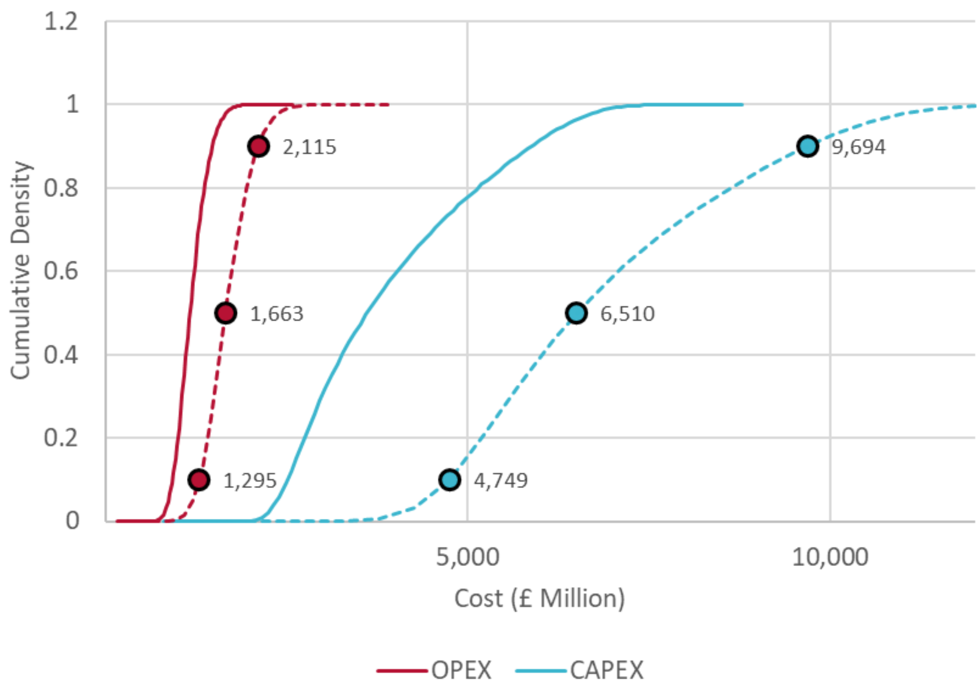


Figure 18 CAPEX and OPEX predictions for an NOAK SBSP system with (dashed) and without (solid) optimism bias. Assumptions used are those from the baseline LCOE calculation. Markers indicate 10th, 50th and 90th percentiles, with their values in £ Million.

	Phase 1 TRL 5	Phase 2 TRL 6	Phase 3 TRL 7	Phase 4 TRL 8	Totals
	5 years	**5 years**	**4 years**	**4 years**	
p10	£125M	£530M	£2,410M	£7,925M	
p50	£135M	£575M	£2,675M	£9,965M	
p90	£145M	£620M	£2,930M	£12,610M	
NPV (p50)	£120M	£435M	£1,740M	£5,655M	**£7,539M**
NPV (p50) Including optimism Bias	£350M	£1,180M	£3,950M	£10,800M	**£16,280M**

Table 5 Development Cost Estimates by Phase. p10, p50, p90 estimates, NPV with and without Optimism Bias

4.2 THE ECONOMIC FOOTPRINT OF A UK BASED SBSP[5]

Establishing a UK-based SBSP system could support a significant economic footprint in the national economy. It is estimated that the net present value (2018 basis) gross domestic product (GDP) contribution (the sum of the direct, indirect and induced GDP impacts) of a UK-based SBSP system is £6,068 million, accounting for leakage (based on stylised assumptions - see Annex C), but not accounting for deadweight nor displacement or substitution effects.[6] Phase 4 of the development programme alone is estimated to contribute £3,345 million (Figure 19). This analysis estimates that for every £1 of GDP generated at the direct suppliers to the

[5] The economic footprint assessment was carried out by Oxford Economics. See Annex C for further details.
[6] A net impact study was not included in the scope of the study. See discussion on methodology limitations in Section 2.4.

project, a further £1.30 of GDP is supported elsewhere in the UK economy as a result of supply chain linkages and wage-funded spending effects. Or put another way, as the total GDP contribution is 2.3 times the direct GDP contribution alone, the 'GDP multiplier' is 2.3.

Despite being delivered over a relatively short timescale (estimated as two years), the capital expenditure programme is expected to support a £1,014million GDP footprint, supporting 26,467 jobs-years[7] in the supply chain. This also infers a GDP multiplier of 2.4, but a higher employment multiplier of 3.4. This higher ratio reflects the fact that GDP per job at the direct suppliers to the project is, on average, much higher than the average across all sectors of the UK economy. By contrast, businesses further along the supply chain to the project, and firms in the consumer-facing induced channel, are more representative of the economy as a whole. Many of the construction phase jobs will be required in space transport services supporting space-lift, which is a key element for the future of a UK-based SBSP, and is duly discussed further in Section 5.1.

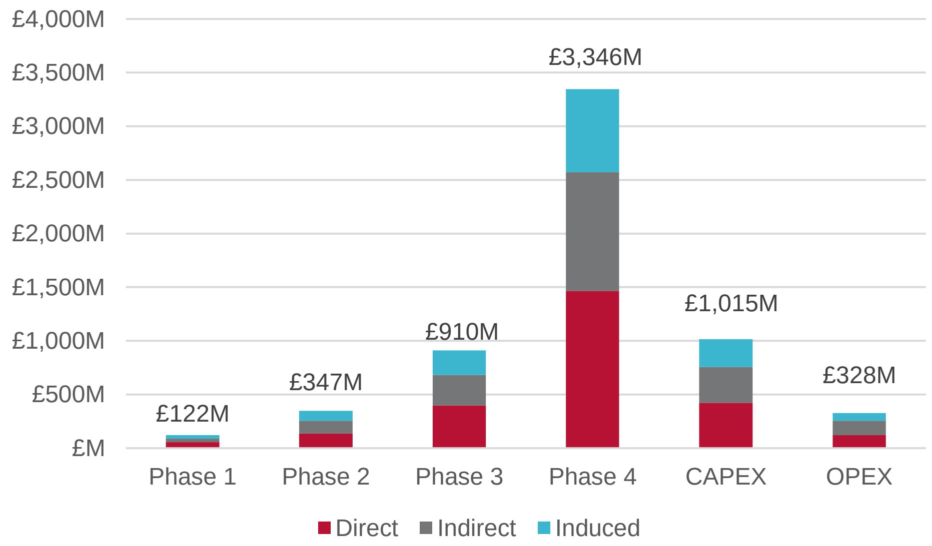


Figure 19 GDP Footprint of a UK-based SBSP System. Source: Oxford Economics

Data presented in 2018 Net Present Value basis

The other development phases (1 to 3) support a further £1,379million in GDP collectively, whilst the operational phase supports £328million. Notably, the operational phase will directly employ an average of 100 staff over the 23-year period, equivalent to just over 2,300 in job-year terms. The total employment impact however, would be significantly higher, at over 10,700 job-years, so that the employment multiplier would be 4.6—with every job in the electricity-generating operation (plus the associated insurance providers) supporting a further 3.6 jobs elsewhere in the UK.

In total, a UK-based SBSP system would provide a direct tax impact of £808million, with the indirect and induced channels contributing a further £561million and £671million respectively. Approximately 143,000 job-years will be supported by a UK-based SBSP system, the equivalent of approximately 5,700 jobs over a 25 year period.

The nature of the work involved means that the labour productivity of activity supported by the project, measured in terms of GDP per job per annum, should be significantly above the

[7] A job-year is one job held for one year, or the equivalent. So ten jobs each held for four years would be counted as 40 job-years, while 80 jobs each held for six months would also count as 40 job-years.

average prevailing across the UK economy as a whole. The comparison for the total economic footprint is set out in Figure 20.

The figures presented here estimate the gross economic impact, including leakage (by considering the value of imports), but do not estimate the value of deadweight nor displacement to determine additionality.[8] Nonetheless, it should be noted that the negative financial NPV of the development programme (see Section 4.4) is a strong indicator that the project would not go ahead without public sector intervention, implying a low deadweight. Moreover, as it is expected that the project would involve individuals working in industries with above-average productivity—even excluding the energy generation activity itself—which would in-turn lead to additional GDP and tax benefits, it is therefore expected that the SBSP programme would yield additional benefits over and above the next best alternative use of the resources committed. A comprehensive net impact study would be required to estimate the value of this additionality. Further analysis of the economic footprint can be found in Annex C.

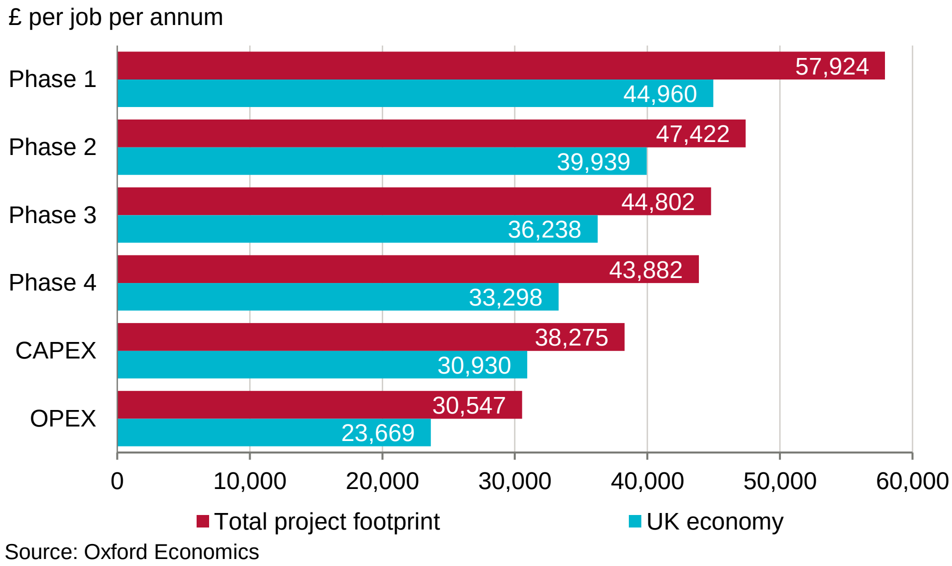


Figure 20 Productivity of all jobs supported by a UK-based SBSP system per phase of activity, compared with UK economy average productivity

4.3 SPILL-OVER BENEFITS

A key characteristic of the investment in development programmes such as this are the spill-over benefits. These are benefits that third parties or society will receive as a consequence of the investments without having to be directly involved in the development programme. Investigations by London Economics [14] identified that spill-overs in the space sector are most often a product of technology transfer via an earth to space to earth transfer pathway. Technologies from terrestrial applications form the basis of development in space applications where their performance is improved to address the high specifications demanded by the space environment. The resulting innovations, typically areas such as low power, low weight, miniaturisation and environmental robustness, are then taken up in terrestrial applications. The space sector therefore has a special role as an integrator and enhancer of terrestrial technologies.

The work carried out in Phase 1 [1] identified the technologies that will be needed for the successful implementation of SBSP. The development programme will enhance the

[8] See Annex C for more discussion on the methodology limitations.

performance of these technologies to meet the particular characteristics of SBSP. However, the resulting enhancements can be expected to have wider application for terrestrial use as well as space programmes. The areas where the envisaged spill-over benefits from the SBSP programme are most likely to arise have been identified. An acknowledgement of the potential for spill-over benefits can encourage early investment in the technology, where the investors can see wider markets within which they can realise a return on their capital, and help to bridge the traditional valley of death that challenges the adoption of early stage technologies.

Spill-over benefits are expected to arise in three broad categories: technology, knowledge and commercial. The specific areas include:

Wireless power transmission; the ability to transmit useful power over significant distances without the need for cables is likely to have utility in a number of markets such as consumer electronics and electric vehicle charging, the development of high power microwave devices will benefit electric switching in power networks and better radar devices.

Semiconductor technology; improvements in high efficiency power electronics leading to high volume, low cost manufacturing processes will benefit a number of electrical power applications.

Photovoltaic technology; improvements in HCPV and the associated semiconductor technologies will benefit other space applications and specialist terrestrial solar collectors.

Inspiring the next generation of students; the developments will encompass a wide range of STEM (science, technology, engineering and mathematics) topics

Market drivers for mass manufacture of space grade electronics; to support the increasing commercialisation of space.

International energy trade via power beaming; SBSP has the ability to deliver power to a wide range of locations, opening up the possibility of international collaboration for shared energy generation and support to provision of energy too hard to reach geographic areas.

Highly modular construction for robotic assembly; the continual drive to reduce manufacturing costs leads to an impetus for robotic assembly and therefore for products to be configured for this approach.

Market drivers for low cost reusable space freight transportation; the market opportunity to encourage space freight companies to establish a commercial service.

Autonomous robotic assembly in challenging environments; the ability to perform autonomous remote operations overcomes significant safety hazards when operating in challenging environments such as nuclear, chemical, offshore and sub-sea as well as in space.

UK centre of excellence for space operations; to support the increasing commercialisation of space.

Figure 21 illustrates when the spill-over benefits could be expected to appear. As the development programme progresses these aspects will become refined and hence the capability and utility of the associated technology will continue to improve.

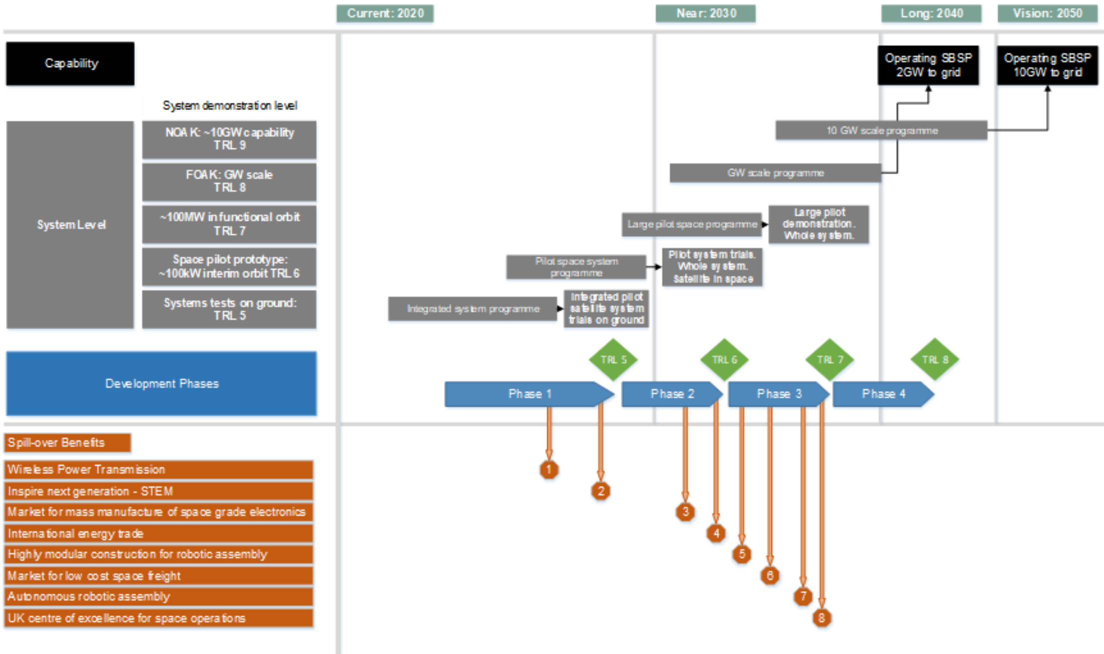


Figure 21 Illustration of when the development programme starts to yield spill-over benefits

4.4 THE LEVEL OF PUBLIC AND PRIVATE FUNDING REQUIRED

An investment into SBSP would be characterised by long development times and a back loaded financial return profile which carries considerable risk and uncertainty. Development of the capability would likely last around fifteen years, a construction period could last five years and so the earliest it would be possible to establish an operational system would be approximately 2040.

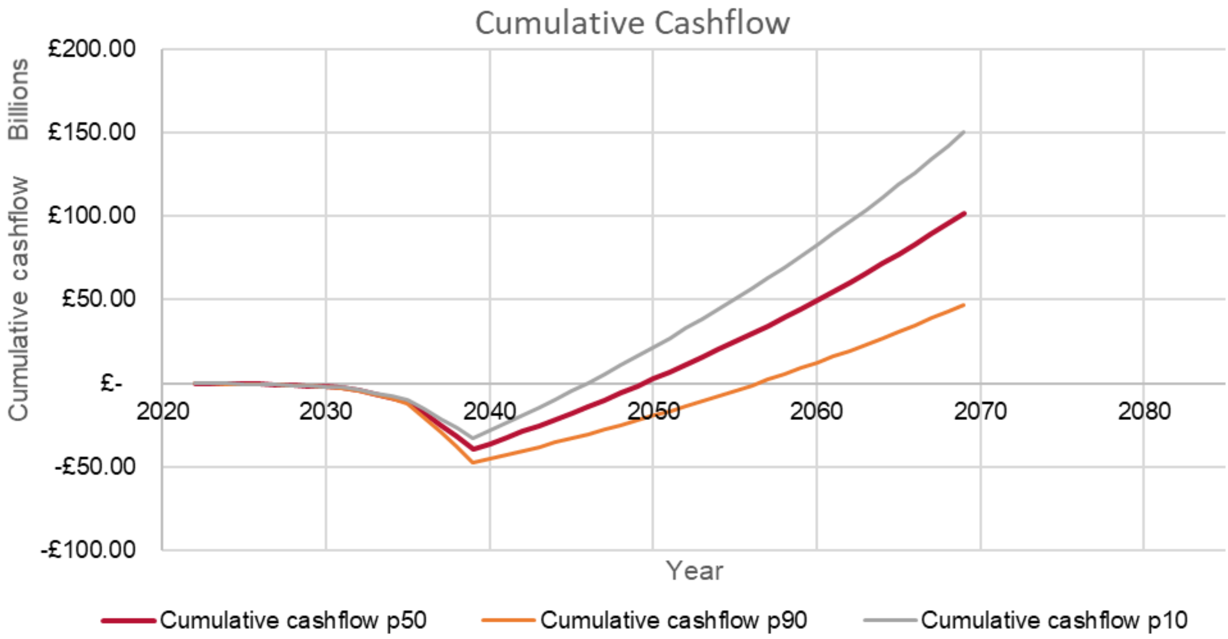


Figure 22 Projected Cash flow Associated with the Development of SBSP

A development profile such as this is fraught with funding challenges. Timescales for a return on investment and the associated risks are significant and therefore finding willing investors will be challenging. Figure 22 demonstrates the cumulative cash flow with optimism bias adjusted costs, taking into account cost and revenue uncertainty. This uncertainty and lack of information about future returns may prevent efficient investment decisions, leading to a market failure. Investments by the public sector could help mitigate some of the programme risk that would otherwise be borne by the private sector and help co-leverage funds to support the development of SBSP. This would help to bridge the near-term financial return uncertainty gap, leading to more efficient investment decisions in the long-run that in turn will contribute towards Government's long-term ambitions of achieving Net Zero by 2050.

To understand the likely payback period of the development, build and operational programme, and the attractiveness of investment, this study predicts estimates of the return on investment using the expected level of energy production and costs derived from the LCOE model, and then draws on examples of other large-scale energy project funding mechanisms and capital costs.

Table 6 provides estimates on the internal and social rate of return and net present value for SBSP taking into account uncertainty around costs and electricity revenues over time and with optimism bias. The IRR could vary between 3.4%[9] and 9.1%[10].

[9] Using p90 development costs, opex, capex and a low strike price estimate (£91.64/MW in 2018 prices) which has been indexed to a Consumer Price Index forecast (2% per annum).

[10] Using p10 developments costs, opex, capex and a high strike price estimate (£174/MW in 2018 prices) which has been indexed to a Consumer Price Index forecast (2% per annum).

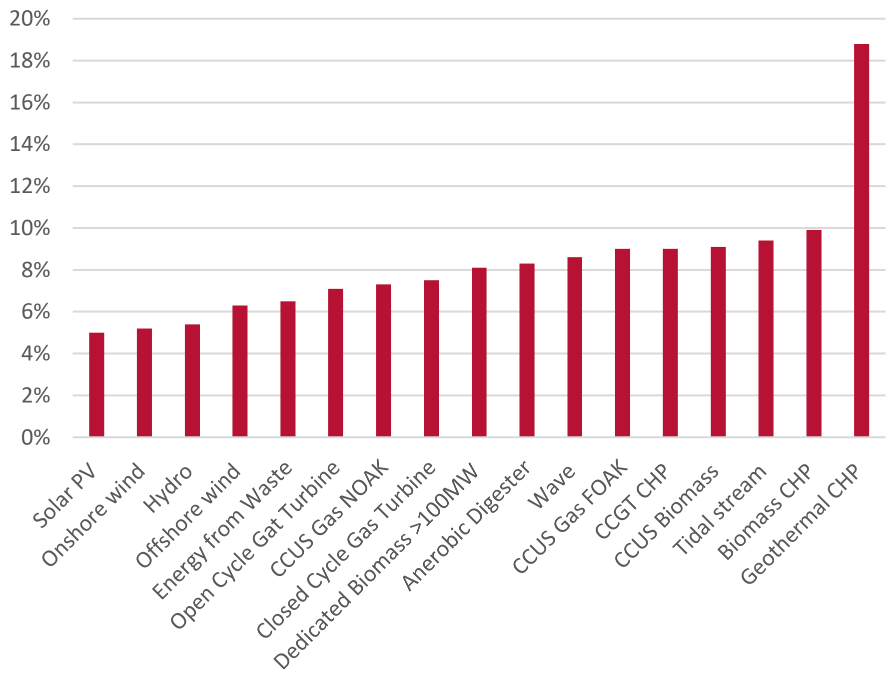
Percentile	Internal Rate of Return (%)	NPV (20% Hurdle Rate) (£)
p10	9.1	-1.8bn
p50	7.4	-3.2bn
p90	3.4	-5.0bn

Table 6 Estimated Internal Return of SBSP

As cited in BEIS' Electricity Generation report (2020) [13], hurdle rates are defined as the minimum financial return that an investor would require over a project's lifetime on a pre-tax basis. In other words, the expected internal rate of return of a project must exceed the hurdle rate of a given industry.

Figure 23 shows the hurdle rates observed in 2018 for an array of technologies generating electricity. The hurdle rates vary from as low 5.0%—where either the risk of project is considered low and/or there are favourable costs of capital (equity and debt financing) —to as high as 18.8% where the inherent risks of projects are presumed to be higher and/or expensive costs of capital in the market.

SBSP is a novel technology without an ultimate owner of the asset. It is therefore too early in its conception to know what the hurdle rate for the technology will be. Nonetheless, hurdle rates in the aerospace industry have been shown to be between 12.5% and 14.5% which implies that there a high risk that SBSP will never be 100% financed by the private sector without public intervention [15], considering an expected NPV less than zero for an aerospace equivalent hurdle rate (Table 6).[11]



[11] The p10 internal rate of return is lower than an aerospace hurdle rate.

Figure 23 2018 Hurdle Rates for some Electricity Generating Technologies taken from BEIS Electricity Generation Report 2020 to show the representative range of values

The hurdle rate of the aerospace industry seems more relevant than others, due to the fact that development projects involve high technology manufacturing which are productionised in factories, as opposed to civil engineering projects such as geothermal CHP. KPMG, in 1991 — before the widespread commercialisation of global positioning systems—stated that the prerequisites for a successful commercial mapping satellite would involve financing with a hurdle rate on the order of 20 percent or lower [16]. Given the lack of a technology specific hurdle rate for space-based solar power, this study assumes a 20% hurdle rate as its benchmark estimate (and considers variations at 10%, 15%, and 25%).

Figure 24 demonstrates the optimum proportion of government funding for the development costs which would help the project to exceed the assumed 20% hurdle rate. If the IRR is higher than the 20% hurdle rate, then the public funding will be providing higher returns than necessary to secure investment (deadweight) and crowd out other projects that could be procured (displacement). When development costs are covered by a central government grant, it becomes optimal to finance approximately 50 percent of the costs through this mechanism. Any higher than that proportion, the incremental increase in grant could result in deadweight and displacement. However, in the presence of optimism bias, the public funding threshold rises to 77 percent to make the project financially viable to private sector investors.

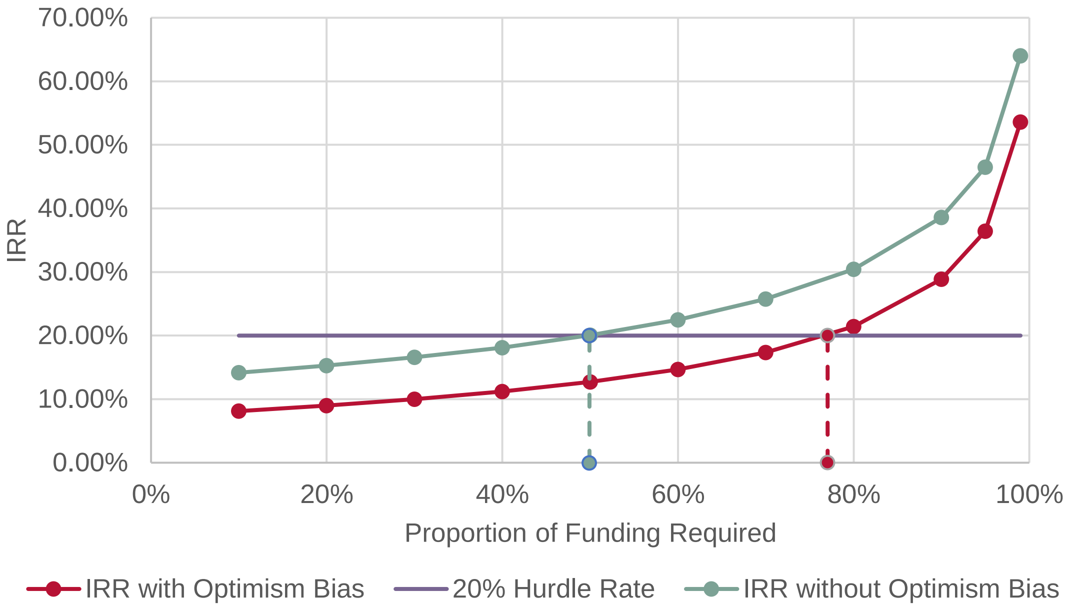


Figure 24 Public Funding Thresholds

Table 7 displays potential private and public funding streams to fund the development across the four phases in view of the public funding thresholds analysis above. With optimism bias, the financial cost of SBSP to the public sector could reach £29 billion and with £9 billion co-leveraged from the private sector. Without the optimism bias adjustments, the public sector's most economically efficient contribution would be £9 billion, with an equal £9 billion contributed from the private sector.

Phase	Phase 1	Phase 2	Phase 3	Phase 4	All Phases
With Optimism Bias					
Public Funding (%)	100	90	80	75	Total
Public Funding Contribution (£millions)	442	1,587	6,875	20,200	29,104
Private Funding Contribution (£millions)	0	176	1,719	6,780	8,675
Without Optimism Bias					
Public Funding (%)	100	80	60	45	Total
Public Funding Contribution (£millions)	153	521	2,274	6,381	9,330
Private Funding Contribution (£millions)	0	130	1,516	7,739	9,386

Table 7: Public and Private Funding by Development Phase

An alternative methodology to explore the funding mechanisms would be for the UK government to set a budget constraint for the public funding that it is *willing* to put forward for the development of SBSP. With a given budget constraint, it is then possible to calculate what the strike price of electricity will need to be, to allow the private internal rate of return to reach 20% (the assumed point at which financial investors will be willing to take on the investment risk of SBSP). Table 8 demonstrates the calculated strike prices for each government budget constraint. As the public funding share of development costs increases, the strike price falls such that the private internal rate of return reaches 20%.

Government Budget Constraint (£millions)	Proportion of Public Funding (%)	Strike Price (£/MWh) (2018 prices)	Hurdle Rate (%)	Private Contributions (£millions)
5,000	14	495.09	20	33,000
8,000	20	448.89	20	30,000
9,000	25	435.48	20	29,000
13,000	33	375.19	20	25,000
19,000	50	286.77	20	19,000
24,000	63	212.28	20	14,000
29,000	**77**	**137.19**	**20**	**9,000**
31,000	**83**	**107.40**	**20**	**7,000**
38,000	**99**	**11.75**	**20**	**0**

Table 8: Setting a Government Budget Constraint and Determining the Strike Price of Energy for the FOAK SBSP System (£millions rounded to nearest hundred million)

This analysis helps to identify at each given government funding level, how price competitive SBSP could be relative to other renewable technologies' strike prices [17]. Figure 25 shows that SBSP becomes more price competitive (including all development phases) with other renewables at a proportion of public funding between 77% and 90%.

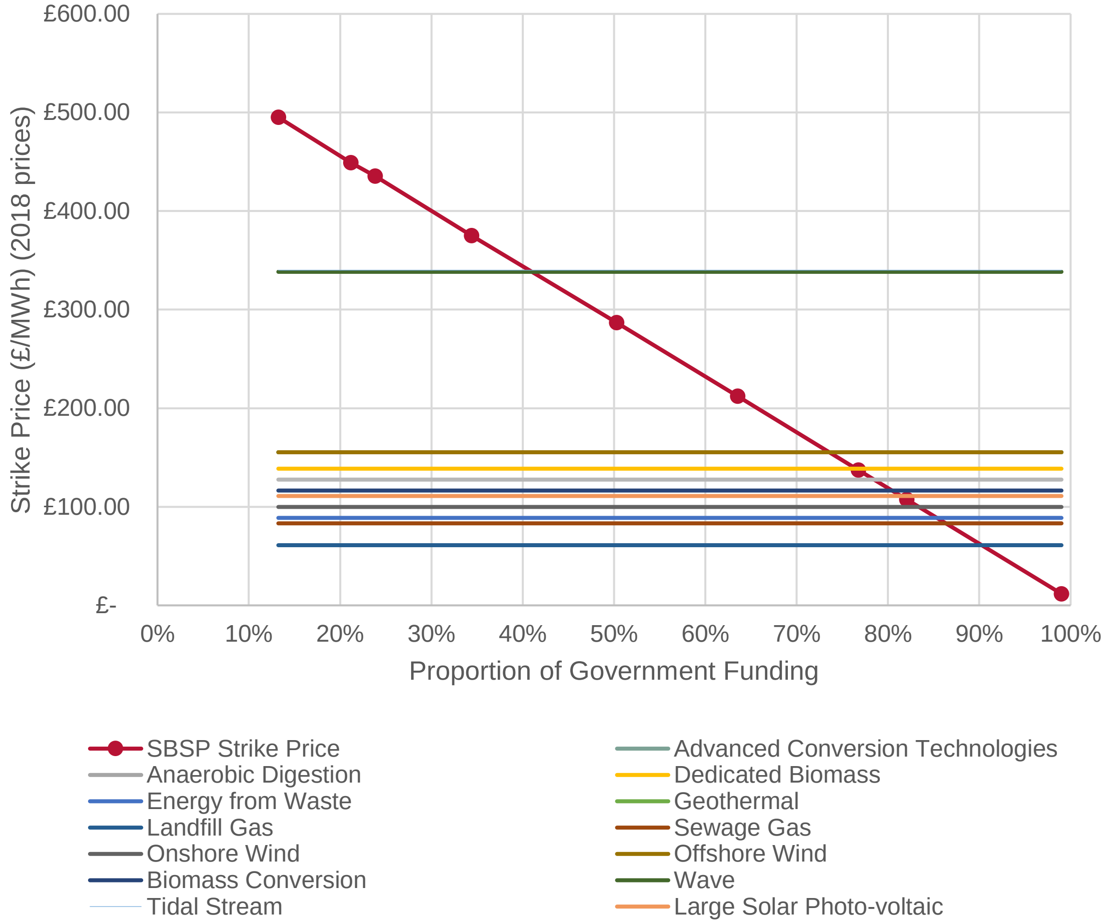


Figure 25: Strike Price of SBSP for a Given Level of Public Funding

4.5 COST-BENEFIT ANALYSIS

By combining the findings from Sections 4.2 and 4.4 regarding GDP contribution multipliers and the level of public funding required for each stage of the SBSP programme it is possible to provide a high-level indication of the likely scale of economic impact on public sector investment into the SBSP programme. The economic footprint analysis by Oxford Economics determined GDP multipliers for each phase of activity, as shown in Table 9.

SBSP Programme Phase	GDP Multiplier
Phase 1	2.2
Phase 2	2.5
Phase 3	2.3
Phase 4	2.3
CAPEX	2.4
OPEX	2.7

Table 9 GDP Multipliers by SBSP Programme Phase. Values calculated by Oxford Economics

Applying the GDP multipliers to the public sector funding contribution—based on the proportions presented in Section 4.4 provides an estimate of the likely scale of economic impact.[12] Net present values (in 2018 prices) are generated using HM Treasury Green Book discount rates for the period in which cost and benefits are realised.

	Development Phase 2022 to 2039								
Scenario	Phase 1 2022 to 2026 (£millions)		Phase 2 2027 to 2031 (£millions)		Phase 3 2032 to 2035 (£millions)		Phase 4 2036 to 2039 (£millions)		BCR
	Costs	Benefits	Costs	Benefits	Costs	Benefits	Costs	Benefits	
Excluding Optimism Bias	122	266	437	886	1,741	2,383	5,653	5,810	1.2:1
Including Optimism Bias	352	767	1,182	2,695	3,948	7,204	10,801	18,502	1.8:1

	Operation 2040 to 2070		
Scenario	OPEX		BCR
	Costs (£millions)	Benefits (£millions)	
Excluding Optimism Bias	719	1,917	2.7:1
Including Optimism Bias	1,013	2,702	2.7:1

Programme Totals			
Scenario	Costs (£millions)	Benefits (£millions)	BCR
Excluding Optimism Bias	8,672	11,261	1.3:1
Including Optimism Bias	17,297	31,871	1.8:1

Table 10 Net Present Value Cost and Benefit Estimates and Associated Benefit-Cost Ratios (BCR)

The analysis (Table 10) suggests a benefit to cost ratio (BCR) between 1.3:1 and 1.8:1 for the first of a kind system, assuming a 20% hurdle rate and associated public sector funding contribution (see Table 7). The BCR at the end of the development phase is estimated at 1.2:1 excluding optimism bias and 1.8:1 including optimism bias, indicating the relative magnitude of gains to society through indirect and induced impacts of initial direct spend only. In addition, there will spill-over benefits resulting from the technologies enabled during the development phases, which are additional to the impact of the direct spend accounted for here, as discussed in section 4.3.[13]

The FOAK system is forecast to be generating electricity from 2040, which will create additional commercial value. An indication of the NPV of energy yield can be calculated using the annual average electricity produced multiplied by the median strike price as described in section 4.4. This estimates a NPV of energy yield for a FOAK system operating for 30 years, commissioned in 2040 within a range of £16bn to £29bn.

[12] Based on a generalised assumption that the gross GDP contribution can be used a proxy for the economic returns on public sector funding considering only the share of direct output that is funded by the public sector.
[13] It should be noted that this high-level assessment is based on gross GDP multipliers. Whilst the analysis in Section 4.2 considers leakage, it does not consider the effect of displacement nor deadweight. See Annex C for further details.

4.6 ASSESSMENT OF UK LABOUR MARKET'S ABILITY TO DELIVER SBSP

Table 11 displays the total average headcount by narrow industry sector through the phases of the SBSP programme. It shows that the electronic components and freight and space and transport services will have to expand significantly in terms of personnel throughout the programme—for the UK labour market to capitalise on the employment opportunity.

Average headcount throughout each phase	Phase 1 2022 to 2026	Phase 2 2027 to 2031	Phase 3 2032 to 2035	Phase 4 2036 to 2039	CAPEX	OPEX
Electronic components (26.11)	0	275	2,660	5,969	705	0
Communication equipment (26.309)	0	0	0	0	10	0
Optical precision instruments (26.701)	0	0	0	0	58	0
Aircraft and spacecraft machinery (30.3)	0	0	31	13	162	0
Electricity production (35.11)	0	14	21	4,314	0	1,511
Construction of commercial buildings (41.201)	0	485	0	0	0	0
Construction for electricity and telecoms (42.22)	0	13	197	678	970	0
Freight air and space transport services (51.2)	1	144	1,872	8,316	4,046	0
Non-life insurance (65.12)	0	30	346	609	0	795
Activities of head offices (70.1)	0	0	0	0	0	0
Other engineering activities (71.129)	0	0	0	0	1,809	0
R&D on engineering services etc. (72.19)	669	1,123	795	705	0	0
Quantity surveying activities (74.902)	0	0	558	1,826	0	0
Total	**600**	**2,293**	**9,929**	**31,205**	**16,187**	**1,827**

Table 11: Average Headcount throughout the Phases by Narrow Industry Sector

To estimate the capacity of the labour market to provide this increase in demand for labour, data is drawn from the Business Register and Employment Survey to estimate the headcounts by industry and how they have evolved over time between 2010 and 2019. The compound average annual growth rate is calculated for total employment between 2011 and 2018 to forecast what the headcount could be when the largest expansion by industry occurs.[14] This is the presumed level of per industry headcount if the sectors continue to grow or reduce organically without the SBSP programme.

Average headcount throughout each phase	Peak Employment as % of forecasted employment
Electronic components (26.11)	57.5%
Communication equipment (26.309)	0.1%

[14] Assuming past trends continue.

Average headcount throughout each phase	Peak Employment as % of forecasted employment
Optical precision instruments (26.701)	0.5%
Aircraft and spacecraft machinery (30.3)	0.2%
Electricity production (35.11)	11.5%
Construction of commercial buildings (41.201)	0.4%
Construction for electricity and telecoms (42.22)	0.4%
Freight air and space transport services (51.2)	273.6%
Non-life insurance (65.12)	1.2%
Other engineering activities (71.129)	0.0%
R&D on engineering services etc. (72.19)	0.4%
Quantity surveying activities (74.902)	0.7%

Table 12: Peak Jobs Estimates as a Proportion of Forecasted Employment by Narrow Sector

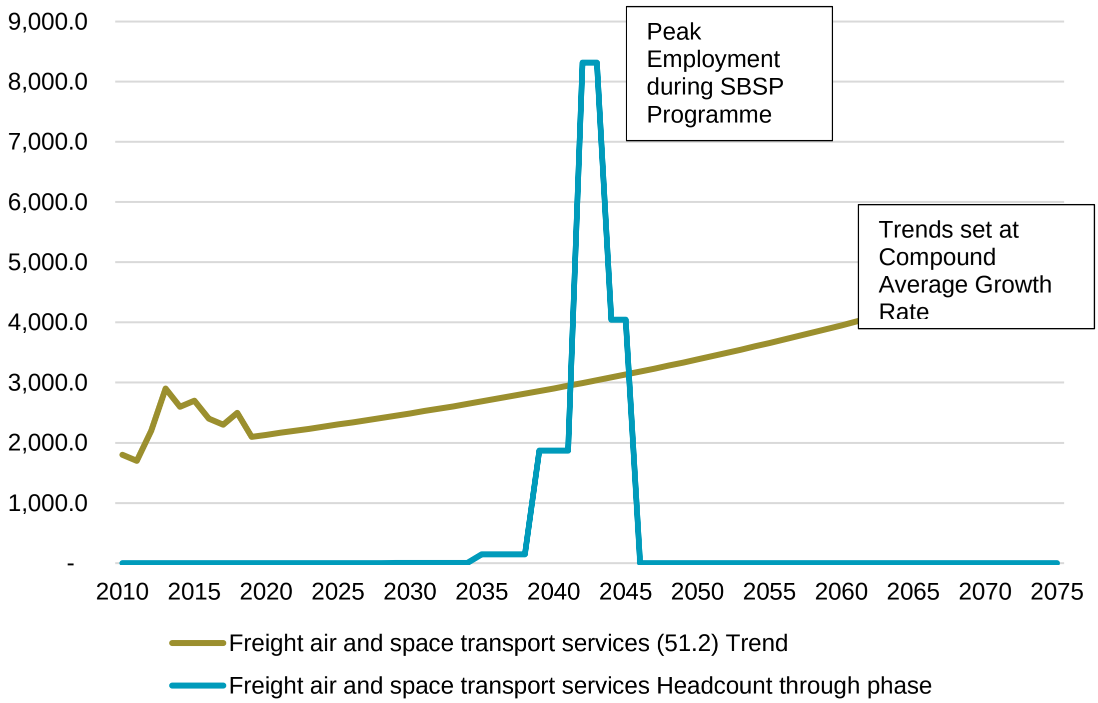


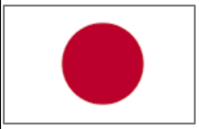
Figure 26: Trends in Growth of Employment and SBSP demand for Labour for Electronic Components and Freight Air and Space Transport Services

Table 12 shows that the majority of sectors are forecast to grow at a level which implies sufficient capacity to meet the presumed level of labour demand brought about by the SBSP programme. However, as shown in Figure 26, the freight and space transport services will need to grow significantly above the forecasted level of employment in 2045 so that the labour is in a surplus of supply when the labour is required, such that it could meet the demand from the sector (as a general assumption and not considering demand from other major infrastructure projects). As a result, there is a risk that the goods and services from these sectors to deliver SBSP will need to be imported unless there is a significant investment in skills and education to increase the domestic supply of labour in this sector. There is an expectation that there will be a vibrant space lift market (which will be required to achieve expected launch costs), and therefore much of the labour requirement will be off-set by importing space lift capability.

4.7 THE ROLE OF INTERNATIONAL COLLABORATION

Building on international engagement carried out as part of this study, and through desk-based research of published information, this section summarises current government supported activities. Several nations have SBSP system concepts and technology development programmes. Much of this work is focussing on the core microwave wireless power transmission technology. The recent paper by Paul Jaffe et al [18] gives a more in-depth discussion on past and current activities.

Policy-led programmes of scale exist in the USA, China and Japan, and there is strong interest in collaboration with the UK from our natural partners. International technical discussion of activities is currently co-ordinated via the International Astronautical Federation (IAF) Space Power Committee, and there is genuine and strong appetite for collaboration from all parties, across boundaries. There is scope for the UK to take a political leadership role, which could be fully open, or focussed on strategic international partners.

Country/Region	Overview of SBSP development and government support
China 	The China Academy for Space Technology (CAST) has a declared SBSP programme and presented a roadmap at the NSS International Space Development Conference in 2015. The Chongqing Collaborative Innovation Research Institute for Civil-Military Integration in China is constructing a facility for SBSP testing. A number of power beaming experiments are being pursued. In March 2021, a new Committee of Space Solar Power was established, to be chaired by Professor Ming Li.
USA 	Substantial defence research, with a $150M program led by Northrop Grumman and the US Air Force Research Lab (AFRL) to develop and demonstrate technology including lightweight sandwich panel PV / RF modules, and lightweight extendable mirrors, under the SSPIDR (Space Solar Power Incremental Development and Research Project. Separately, the Naval Research Lab (NRL) is conducting power beaming experiments in space on the X-37B spaceplane. There is currently no civil energy policy from the Department of Energy related to SBSP
Japan 	Since the 1980s Japan has undertaken well-funded research into SBSP, primarily focussing on WPT, and including in-space experiments. Japan has established space solar power as a national goal enshrined in its Basic Space Law, and JAXA has a roadmap to commercial SBSP. JAXA successfully demonstrated kW scale wireless power transmission in 2015.
South Korea 	A number of power beaming activities are being pursued by KERI (Korea Electrotechnology Research Institute) and private organisations.

Europe 	Recently ESA issued a small-scale call for ideas to research technologies related to SBSP
Canada 	There is interest at ministerial level, but no government supported activities.
Australia 	There is interest within the Australian Space Agency and at ministerial level, but no published government supported activities.

5. CONTRIBUTION TO UK STRATEGIC OBJECTIVES

This chapter of the study compiles insight gleaned during engagement with key industry stakeholders and reviews of existing information regarding the potential contribution of SBSP to the UK Government's strategic objectives, as set out in BEIS' single departmental plan [19].

5.1 DELIVER A SUBSTANTIAL CONTRIBUTION TO NET ZERO BY 2050;

SBSP could de-risk the UK's pathway to Net Zero, making a substantial contribution to its clean energy future by 2042, helping to ensure the UK has a reliable, low cost and clean energy system (strategic objective 4).

In support of the government's commitment to Net Zero carbon emissions by 2050 a number of organisations have investigated in detail the measures that would be needed to meet that commitment. The Climate Change Committee has published its 6th Carbon Budget which explores a number of potential pathways. The Energy Systems Catapult's report 'Innovating to Net Zero' builds on the Climate Change Committee's work by understanding how important individual technologies are in meeting the target. The National Grid uses a series of Future Energy Scenarios to understand how Net Zero can be achieved. The Department for Business, Energy and Industrial Strategy (BEIS) uses a series of scenarios in the Electricity Generation Costs report to present its energy market analysis in support of the policy making in the progress towards Net Zero.

Whilst these approaches tackle the problem in different ways they all use sophisticated models to predict the future demand across the different energy sectors, such as transport, heat and electricity, and then explore the impact that different combinations of energy source and energy use could have on meeting the demand. Assessing the ways that the models meet the future demand allows the analysts to highlight the impact that alternative solutions will have on users, the changes that might be needed in national infrastructure and the reliance on behavioural change in society.

All of the investigators recognise that there is a degree of uncertainty in the ability of the pathways and scenarios to achieve the target of Net Zero by 2050. Reducing carbon emissions will rely on a portfolio of generation technologies, including variable renewables, and other low carbon generation technologies together with the ability to respond to flexible demand and use of energy storage. The pathways rely to a certain extent on the development of emerging technologies such as increasing the capture efficiency of carbon capture and storage, development of a hydrogen economy and ongoing cost reduction of nuclear plants.

None of the models appear to explore the contribution that SBSP could make to these pathways or scenarios. As discussed in section 5 of the Phase 1 report [1] SBSP presents a combination of characteristics that complements other generation technologies. The work carried out in Phase 2 and discussed in this report has highlighted that the predicted LCOE for SBSP is competitive with other generation technologies. Therefore SBSP has the potential to support alternative pathways to Net Zero. It is recommended that the existing models are used to explore the contribution that SBSP could make to the pathways and scenarios, and provide a quantitative analysis of the scale of SBSP that could be integrated into the grid.

5.2 DELIVER AN AMBITIOUS INDUSTRIAL STRATEGY

The SBSP development programme provides an opportunity for the UK Government to realise its Industrial Strategy ambition to position the UK at the forefront of future industries and emerging sectors. Specifically, the ambition to maximise the advantages for UK industry from the shift to clean growth. Should the UK develop SBSP technology, it could provide export opportunities both in licencing the technology and beaming energy to other nations. This would contribute to the government's objective to position the UK as the world's most innovative economy by promoting investment in science, research and innovation (strategic objective 1.3). Considering the size of the SBSP development programme, the government would make a significant contribution towards supporting world leading science and innovation by agreeing a roadmap to meet the 2.4% R&D investment target by 2027.

SBSP would greatly enhance the UK's capability to operate in the Space domain; it would provide a flagship Space programme to grow our share of the global space market, a core Government target; it would align with our drive to develop in-orbit service and manufacturing capability.

Moreover, the UK has existing strengths in research, development and manufacture of core technologies required for SBSP. By committing to the SBSP development programme, the Government could realise its ambition to support economic resilience and future growth. During this study, engagement with UKRI EPSRC on relevant research activities identified 19 current EPSRC research activities closely aligned to SBSP, covering the fields of:

- Robotics, including in irradiated and hostile environments
- Autonomous assembly and maintenance in Space
- In-orbit manufacture
- Lightweight materials and structures
- Radiation hardening
- Wireless power transmission
- Space based power conversion

Similarly, the UK Photonics Leadership Group, illustrated that the UK is a leader in both design and manufacture of the high concentration photo-voltaic (HCPV) and wider semiconductor and power electronics technology. The Group advised that the high volume manufacturing required for an SBSP programme could be established competitively in the UK, without the need to outsource. Core technologies where the UK have existing strength include:

- HCPV
- High volume semiconductor manufacture
- Lightweight space structures
- Wireless power transmission
- In orbit servicing and manufacturing
- SBSP environmental studies
- Spacecraft electric propulsion

This reinforces the economic benefit to the UK of pursuing SBSP and establishing competitive manufacturing of SBSP in the UK.

It was noted that manufacturing processes require very lengthy lead times, and consideration should be given to industrialisation and supply chains early in the development programme.

5.3 MAXIMISE INVESTMENT OPPORTUNITIES AND BOLSTER UK INTERESTS AS WE LEAVE THE EU

SBSP is an ambitious concept but the rewards of a highly scalable source of renewable energy could help the Government to build the profile of the UK on the international stage (strategic objective 2.4). The UK could reinforce its global leadership in the pathway to Net Zero and clean air, with opportunities for international collaboration, another important priority for post-Brexit Britain.

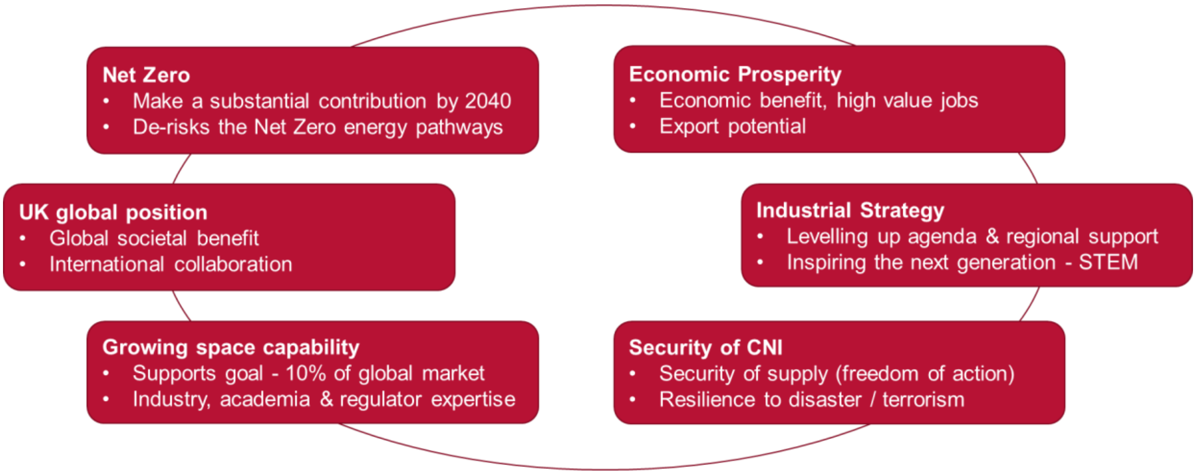


Figure 27 Strategic contributors of SBSP

SBSP would provide the UK with a sovereign energy capability, with no reliance on other nations. This offers greater freedom of action in political and diplomatic strategy.

The concept appears to have good resilience to disaster or hostile acts, though this would need further study.

5.4 SUPPORT UK PROSPERITY AND HIGH VALUE JOBS

The government aims to support economic resilience and position the UK to seize opportunities for economic growth (strategic objective 3). SBSP development could help our economic recovery as a major infrastructure programme, providing high value jobs, economic benefits and spill over benefits to boost the economy.

SBSP has potential to create opportunities and prosperity across the whole of the UK (strategic objective 1.5). Core SBSP semiconductor and HCPV technology and manufacturing could be located in regions such as South Wales, Northern Ireland and the North East, where there is already established optoelectronic and microwave component manufacturing. This could produce high value development and manufacturing jobs to support the Government's 'levelling up' agenda.

Growing the next generation of engineers is vital to our economic growth, and SBSP would be an inspirational programme for the UK attracting the next generation into STEM subjects, and the Aerospace, Space and Renewable Energy sectors. It would also help the UK to retaining our best and most experienced engineers in the UK, avoiding a brain drain to other countries.

Unique differentiators

The UK has a number of specific technologies and IP offering differentiation from other nations. Several organisations and individuals in the UK are very well engaged in SBSP research and design; two are members of the IAF Space Power Committee, the leading organisation co-ordinating international SBSP activities.

Ian Cash of International Electric Co. Ltd, Harwell, is the designer of the CASSIOPeiA concept, one of the leading and most competitive SBSP concepts and included in this study.

Reaction Engines Ltd is developing the SABRE air breathing rocket engine with the support of UKSA and ESA. This is the core technology for a fully reusable spaceplane.

The right innovation environment

The UK offers an excellent environment to lead the development of SBSP. We have leading enterprises in both the Space and Energy sectors, world leading universities and research sectors.

We have a strong blend of prime contractors and innovative technology companies in the space and manufacturing sectors, and this is backed up by a strong financial sector.

Finally, the UK, via the UKSA and CAA (Civil Aviation Authority) is a leader in the development of Space regulation. International negotiation and proportionate development of regulations will be an important factor in encouraging innovation and enabling SBSP.

6. SBSP RISKS AND ISSUES

This section discusses space transportation, which is the dominant cost driver, and also poses substantial logistic and market challenges. It also provides a broader summary of the development risks for SBSP.

6.1 SPACE TRANSPORTATION

6.1.1 The need for fully reusable launch systems

Launching the thousands of tonnes of SPS hardware is a dominant cost factor in the overall manufacturing and assembly cost. The cost of rocket fuel is a tiny fraction (typically << 1%) of the cost of the rocket hardware, and the route to low cost space access thus lies in fully reusable heavy lift launch systems.

SBSP space transportation systems must be capable of high launch tempo. If for example, just one 2,000 + tonne SPS is to be commissioned per year, a launch capacity of around 50 tonnes per week would be indicated. Current projections [20] for the total tonnage of satellites to be launched globally, into all orbits, between 2019 and 2028 suggest around 400 tonnes per year on average, or 8 tonnes per week.

Thus the launch demand from a modest SBSP programme alone would be around 6 times the current global demand for launch services.

6.1.2 Characteristics required

Two systems have been considered which bracket the likely range of cost figures for the future space launch market:

- A future Reaction Engines SABRE powered horizontal take-off and landing spaceplane, fully reusable and either single stage to orbit or two stage to orbit. A technology demonstrator of the SABRE engine is currently being developed together with the UK Space Agency;
- The SpaceX Starship which in 2021 is in advanced flight test, featuring fully reusable first and second stages, and with the capability of refuelling in orbit;

An essential characteristic to achieve both low cost and high launch tempo is that systems are operated like a commercial freight airline. This requires minimal maintenance and rapid turnaround between flights, with a comparatively small ground support operation. Systems need to be fully reusable, and not simply refurbished. NASA’s Space Shuttle was an example of the latter, requiring an expensive and time consuming overhaul after every flight.

Both the above systems are designed to require only modest maintenance / refurbishment between flights, and deliver 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.

In practice the reliability, flight rate and maintenance costs are key drivers of the launch cost / kg. Vertical launch (VL) systems have a failure rate of up to 5%, which drives the insurance costs and can introduce programme delays. A horizontal launch spaceplane potentially offers more abort options than vertical launch systems, and the reliability is predicted to be up to 100 times improved compared to VL systems, with a 0.05% failure rate. This would drive down insurance and operational costs.

Until these systems become mature technology and start routine operations, there is a significant degree of uncertainty on cost figures.

6.1.3 Launch UK

Launch UK is focussed on growing the launch market for small payloads, from UK spaceports. This is a rapidly growing market and will provide the UK a sovereign capability to launch small satellites. This UK capability has not been considered for SBSP because the launch tempo and costs of smaller expendable systems, even the Virgin Orbit One due to operate from Spaceport Cornwall, are unlikely to be compatible with the requirements of an SBSP programme.

The operational orbits are another consideration. The UK is well positioned for launch into high inclination orbits, but a typical orbit for SBSP is GEO, which requires equatorial launch sites to minimise the Delta V and launch costs. There are however some SPS architectures (such as CASSIOPeiA) which can operate in elliptic orbits with high inclinations. Studies by Cash of IECL suggest that a four satellite constellation in a Cobra tear drop orbit would provide continuous (24/7) base load power delivery for the UK and with similar economics to the GEO configuration. This configuration could in principle be launched from the UK, with a future launch system such as a SABRE powered fully reusable spaceplane. A future reusable Spaceplane might in principle operate from one of the identified horizontal launch Spaceports, at Newquay in Cornwall, or Prestwick, near Glasgow.

6.1.4 Heavy Lift market resilience

There are a number of companies developing reusable low cost heavy lift launch capabilities, including SpaceX, Blue Origin, and Rocket Lab. As shown above, it is likely that the establishment of a national or international SBSP programme would provide a huge market demand for fully reusable low cost space transportation, and accelerate the development of these and successor systems.

Whilst SpaceX may form part of the solution, it would be unwise to rely on a single commercial company being around in 20 years' time to provide these services.

Europe is currently developing the next expendable vertical launch system, Ariane 6, which will be very capable but too expensive for SBSP, and unlikely to deliver the required launch tempo. A next generation European launch system will need to be fully reusable to compete with the next generation of systems developed by the private sector and forecast to be available in the 2040 timeframe.

Although the market trends are encouraging, the current lack of a vibrant and competitive launch market is considered to be a significant risk to the commercial development of SBSP. Early consideration is recommended of the UK strategy for collaborative development or procurement of fully reusable heavy lift capability.

6.1.5 Business case for a SABRE powered spaceplane

The UKSA is supporting the SABRE air breathing spaceplane engine technology development programme, for which SBSP is an identified market. However there is currently no spaceplane programme identified for SABRE. A collaborative European spaceplane development, centred on SABRE engine technology would appear to be a logical solution to both meet the forecast demand for SBSP launch capacity, and at the same time establishing a future reusable European launch capability.

A market study is recommended to assess the demand for SBSP launch capacity from an international SBSP programme, together with the associated business case for a European collaborative spaceplane development programme, centred on SABRE technology.

6.2 SBSP SYSTEM DEVELOPMENT RISKS

Using a systems engineering, through life approach the risks associated with the development of SBSP and their mitigation have been assessed qualitatively. At this stage of the analysis the severity of risk and impact have not been evaluated. This assessment is based on literature review, workshop discussions and consultations with individual experts. The risks are broken down into eight categories below:

6.2.1 Technical – space segment

Issue	Consideration	Recommendation
System specific power	The latest concepts claim high power / mass ratio which is central to the economics. This performance depends on both the elegance of the concept architecture, and use of lightweight integrated photo-voltaic and RF sandwich panels, mirrors and structure. However these concepts are only at design study stage, and this system performance has not yet been demonstrated in hardware.	Key technologies are currently being developed and demonstrated at module scale in the space environment [18]. The UK should establish its own technology development programme, informed by a system concept study.
Power beaming efficiency and pointing accuracy	The mass and cost depend upon achievement of the required power beaming efficiency through the energy chain. Tests have demonstrated the required efficiency at subscale and short distances, such as the 1975 Raytheon Goldstone test, which is encouraging. However a complete end-to-end demonstration, including the necessary pointing accuracy and retro-directive control has not been demonstrated in the space environment over very large distances from GEO.	Early research should focus on the power beaming as core technology that needs to be demonstrated in an operational environment, and at scale.
Radio Frequency (RF) interference	The design of the microwave beam forming is important both to minimise interference from side lobe radiation, and to maximise energy transfer efficiency. The effect of side lobes on other satellites has not been studied.	Analysis is required of the RF beam forming and the operational impact on other satellites.

Issue	Consideration	Recommendation
Base-load power and the rotational mismatch	SPS concepts must address the rotational mismatch between the sun pointing and earth pointing elements if they are to provide continuous base load power. Different SPS concepts tackle this in a number of ways, with consequences for the technical risks, mass and reliability. CASSIOPeiA is an example of an elegant base load solution requiring no moving parts (fully solid state), and with no redundant parts, i.e. all modules providing full power through the whole orbit (minimum mass).	This is a central requirement of a base-load SPS design. The design solution is key to the system performance, cost and risk.
Power distribution	Distributing the Gigawatts of power from the solar panels to the transmitters is a challenge for all SPS concepts. Some (e.g. MR-SPS) have long conduction path lengths and may require heavy cabling to keep resistive losses down. Other hyper-modular concepts (SPS Alpha, CASSIOPeiA) address this with local distribution at the module level, and very short path lengths.	Minimising the mass of power distribution is a key issue, closely tied up with the thermal management aspects.
Thermal management	The latest SPS concepts address both the transient and steady state thermal management challenges in their design without requiring large radiators. Achieving reliability targets requires component temperatures to be kept within operating limits.	Thermal design and performance requires early consideration as part of the concept studies. Use of a digital thermal twin is recommended to ensure thermal management risks are understood and addressed.
Atmospheric scintillation	The RF beam could be sensitive to ionospheric scintillation, diffracting and scattering the radio signals, and thus reducing the efficiency of power beaming. This would need to be studied. Adaptive technology could mitigate this risk, using established techniques analogous to adaptive optics used for astronomical telescopes.	This requires study and experimentation as part of a demonstration programme.

Issue	Consideration	Recommendation
Maturity of system requirements	Though the latest concepts appear well considered, the UK requirements have not yet been developed. These may affect performance, regulatory, safety, security, environmental management and resilience considerations, which could in turn introduce new constraints and costs.	As an early priority, the UK should develop a set of SBSP User and System Requirements, in parallel with a concept design study. This would serve as a foundation to understand the cost and risk for any subsequent design and development programme.
Scale	The SPS is an order of magnitude larger than any other spacecraft, and that in itself is likely to present integration challenges which are not yet well understood.	A structured programme of design, research, modelling, and technology demonstration is required to characterise the system integration risks.
Complex dynamic behaviour	The large sparse SPS structure is likely to have very low stiffness. The interaction of the structural dynamics and orbital mechanics is not well understood and could cause challenges for attitude control and station keeping.	Research and analysis is required to understand the interaction between structural dynamics and orbital mechanics.

6.2.2 Technical – ground segment

Issue	Consideration	Recommendation
Rectenna siting	The rectenna needs to occupy a very large contiguous area; a 2GW rectenna would be over 7km wide (W-E direction) and 14km high (N-S direction). For the UK, this may mean that the rectenna needs to be located offshore. It may be possible that the ground under the rectenna could be used for other purposes such as agriculture, but this would require further studies into the effect of the microwaves. It should be noted that the RF intensity would be lower than someone using a 5G phone, but that existing specific absorption rate (SAR) safety standards are based on low power devices located close to the head. Hence, although there is expected to be no safety issues, further work is required to set safety standards for distributed microwave beams.	Explore possible sites for the rectenna, taking into account the size of the rectenna and the opportunities for grid connection, coupled with a more detailed study into the safe limits for microwaves.

6.2.3 Assembly, Commissioning and Supportability

Issue	Consideration	Recommendation
Autonomous in-orbit assembly	Advances are required in autonomous robotic systems, including in-orbit construction and assembly. Whilst in-orbit servicing capabilities are rapidly maturing, the requirement for assembly of these very large structures may well be different from the current focus of research, and these requirements are not well defined.	Study the requirements for in-orbit assembly and servicing in parallel with concept design studies. Establish a development programme for the autonomous robotic assembly systems.
Operational life	Competitive economics depend on a long operational life, typically 25 years or more. The SPS designs need to be highly reliable in the GEO environment, with sufficient station keeping propellant or a means of automated refuelling.	The service life is a core requirement, and the design and operational concept to achieve this should be a central part of the early design studies.
Availability, reliability and maintainability	High system availability is a central requirement for a base-load energy source. The SPS requires effective Fault Diagnosis, Isolation and Recovery (FDIR), and a cost effective means of servicing through autonomous robotic servicing missions. The system architecture needs to consider how to address periods of earth shadowing, and the ability to undertake servicing whilst the SPS is beaming power. Some concepts (e.g. CASSIOPeiA) propose a constellation of satellites in elliptical orbits that would avoid the two short periods of eclipse at the spring and autumn equinox.	System availability and reliability are core requirements. The supportability strategy needs to be identified at the outset and built into the system design.

6.2.4 Safety and Environmental

Issue	Consideration	Recommendation
Environmental Impact	An environmental impact assessment was beyond the scope of the current study. Other studies have suggested that the carbon payback period, to offset the energy used in manufacturing and launch, is in the order of six months. However this would need to be confirmed. SBSP will contribute very slightly to heating of the earth and atmosphere. From discussions with University of Strathclyde environmental experts, this is likely to be inconsequential, but needs proper study. The environmental impact needs proper assessment as part of a design and development programme.	Undertake an assessment of environmental risks, impacts and mitigation, including the carbon payback period, heating effects, and siting of the rectenna.
Long term risk to public health	Safety is assumed to be inherent from the safe beam power density levels at the rectenna. Whilst no safety concerns have been identified, the long term safety would need to be properly studied and technical standards established for distributed microwave beams. The Japanese have done safety studies on microwave exposure.	Embed the assessment of through life safety into the concept design and development studies. This will be an important element for societal acceptance and regulatory approval.
Risk to spacecraft and aircraft	The risk to spacecraft and commercial aircraft flying through the energy beam has not been evaluated. The risk is more likely to involve temporary disruption of communications rather than system failure. Mitigation strategies could include airspace control measures, with danger areas around the beams, and temporarily switching off the beam during transit of vulnerable spacecraft.	Early study of the Electromagnetic Compatibility issues for other spacecraft and aircraft is required to inform the system architecture and concept of operations.
Solar PV uses rare earth elements	The source and sustainability of raw materials needs to be identified.	This aspect of sustainability requires study, if SBSP is to become widespread and

Issue	Consideration	Recommendation
	Some SPS concepts use High Concentration Solar PV (HCPV), which yields very high output and good efficiency per unit area, making efficient use of the solar cells.	scalable as a major source of clean energy for the world. Development of HCPV would also assist material availability for terrestrial solar.
Decommissioning	Whilst a number of ideas have been proposed, there is no clear method established for decommissioning these very large satellites in high earth orbit.	Studies are required to identify sustainable and responsible methods of decommissioning the SPS at end of life.

6.2.5 Economics and Market

Issue	Consideration	Recommendation
Evaluation of the system economics and risks	Achieving a competitive LCOE is a key challenge. Currently there is little analysis of the end-to-end system operation, servicing, failure scenarios, life extension or the impact of off-design performance.	A parametric performance model is required to support the design and evaluation process, providing insight into technical, operational, availability, cost and economic aspects. This should model dynamic events as well as steady state operation.
Energy scenario modelling	SBSP has some unique characteristics as a source of clean base load energy. However the concept has not yet been studied using current energy models to assess how SBSP might integrate with a future UK clean energy mix. This is important to understanding the market demand for SBSP in the UK.	Undertake energy modelling to evaluate and quantify the contribution of SBSP in a future UK clean energy mix.
Availability of low cost fully reusable space launch	There is a risk that the necessary low cost space transportation is not available. A vibrant and resilient launch market would require at least two competing providers, to assure the necessary high tempo programme of launch could be procured, and at the right price.	The Government should establish a clear strategy on the UK's long term role in encouraging the fully reusable space launch market.

Issue	Consideration	Recommendation
Competition from other renewable technology breakthroughs	If other technologies, such as terrestrial solar in the desert, or large scale battery storage become technically feasible and economic, this could undermine the business case for pursuing SBSP. Currently there are major challenges with these schemes.	The economic case for SBSP should be periodically re-examined against other maturing technologies.
No existing mechanism for international trading of SBSP generated energy.	There is potential to supply and trade SBSP generated power to numerous countries, which would add to the market attractiveness of SBSP.	To explore potential market opportunities and international partnerships.

6.2.6 Industrial Capability

Issue	Consideration	Recommendation
UK industrial capability and production facilities	The economics of SBSP depend on high volume automated manufacture and assembly of modules in dedicated factories. The lead time to industrialise semiconductor and electronics manufacturing processes is considerable. The findings are encouraging in that the UK has strength in all the core technology areas, as well as competitive volume manufacturing of semiconductor technology.	Give early consideration to manufacturing capability and industrialisation as part of the development roadmap.

6.2.7 Security and Resilience

Issue	Consideration	Recommendation
Technical failures	The concepts studied address resilience by avoiding single points of failure, and the hyper-modular architecture of the SPS-Alpha and CASSIOPeiA concepts provides for graceful degradation, with maintenance by replacement of failed modules.	The system architecture needs to be designed with resilience as a core requirement. Address functional safety and resilience to failures through use of FMECA (Failure Modes, Effects and Criticality Analysis) early in the design process.

Issue	Consideration	Recommendation
Damage from space debris	Some thought has been given by concept designers to the sequence of orbit raising and assembly to avoid congested orbits where there is highest risk of space debris. The risk of one collision spreading further space debris (Kessler syndrome) would need study. The hyper-modular architecture, and very lightweight sparse structure mitigate this risk to some extent. Avoidance of single failure points allows local damage and graceful degradation without causing failure of the whole Solar Power Satellite.	This needs further study as part of the system design.
Van Allen Belt radiation	As with the space debris risk, consideration has been given to the sequence of orbit raising and assembly to avoid extensive loiter in the harsh environment of the Van Allen belts. Assembly could be done just above the inner VA belt, before raising to GEO.	This needs further study as part of the system design.
Space weather events	A large solar flare or Carrington event could cause the SPS to fail, partially or completely. It may not be practical to harden the modules sufficiently against extreme space weather events.	This is also true for terrestrial power grids. Design studies would be needed to optimise the design strategy for resilience in terms of hardening vs repair and replacement.

Issue	Consideration	Recommendation
Hostile actor attack	Risks could include a hostile actor attacking the Solar Power Satellite with a kinetic, blast or EMP (Electromagnetic pulse) weapon in space. The SPS is a large, sparse structure, and with its distributed hyper-modular architecture, would be difficult to degrade substantially by a kinetic energy weapon. Discussion with Director Space for the UK MOD suggested that this risk is the same as for any Critical National Infrastructure, in that an attack of this kind is a violation of international treaties. It would be an escalation of hostilities amounting to a declaration of war.	Physical protection of this CNI asset needs to be addressed as part of the System requirement and design. Defence has a strategic interest in Space Situational Awareness (SSA) – understanding the position and intent of other nation's space assets. There may be requirements to include SSA sensors on the SPS.
Physical and Cyber Security	The design of SBSP will need to address cyber and physical security, in a similar manner as for other terrestrial CNI. The encrypted pilot beam and communication links provide control and secure communications with the SPS. The rectenna is a large structure, and would need protection, though its comparatively simple structure and lack of single points of failure would make it difficult to disrupt. The placement (offshore / onshore) may be influenced by security considerations. The satellite and power control ground station are relatively small self-contained facilities which would be easy to secure.	Security, including cyber security should be a core requirement addressed during the design and development programme.

6.2.8 Political and International

Issue	Consideration	Recommendation
Spectrum allocation	The allocation of RF spectrum bandwidth in the 1 – 10 GHz range is essential, and will require international negotiations.	An early part of any SPS development should include a process of engagement with the ITU (International Telecommunication Union).

Issue	Consideration	Recommendation
Orbit congestion	Geostationary Earth Orbit, the most commonly suggested orbit for SBSP, is occupied largely by communications satellites. International negotiation would be required to integrate very large Solar Power Satellites into GEO.	The issue of available orbital slots requires early study and international negotiation.

6.2.9 Societal

Issue	Consideration	Recommendation
Public acceptance of new technology involving power beaming	As with other technologies such as Fracking and 5G, there may be public concerns about the safety, environmental impact and affordability of SBSP. Some concerns could be mitigated by positioning the rectenna in offshore locations, to avoid disrupting local communities, and to address any perceived safety concerns. A well-structured public engagement and information campaign will be required at the right point, to gain broad public and political acceptance.	Plan a public engagement and information campaign as part of a development programme.

7. CONCLUSIONS

The challenges, risks, and resultant recommendations identified in this report are intended to inform the next steps.

7.1 KEY FINDINGS

The analysis presented in this study has found that:

1. A successful SBSP programme could provide a low carbon source of baseload electricity that is economically competitive with other forms of energy generation technologies. The 50th percentile LCOE of the SBSP system considered is £50/MWh. The 10th to 90th percentile range is £35MWh to £79/MWh.

2. **The LCOE estimates are highly sensitive to space-lift costs.** To mitigate this, a range of space-lift estimates have been used in the LCOE model. The most feasible way to realise low space-lift costs would be through a competitive, commercial, reusable space launch market, with characteristics similar to the commercial freight airline industry.

3. **SBSP requires a substantial development programme that could be achieved over an 18 year timeframe.** The cost of the development programme required to mature the technology is highly uncertain at this stage of design maturity. Nevertheless, initial estimates suggest a NPV median cost of the order of £7.5 billion, rising to £16.3 billion taking optimism bias into account.

4. A Public funding contribution of £29 billion is necessary while co-leveraging a further £9 billion of private funding to cover the development costs of raising the TRLs of the constituent systems of SBSP. This investment will help ensure that the first-of-a-kind SBSP system is commercially viable and price-competitive relative to other renewable technologies and facilitate the creation of a commercial market for nth-of-a-kind SBSP systems.

5. **SBSP requires significant labour demand across all its phases.** The majority of key sectors are expected to grow in line with forecasted labour demand. However, the freight air and space transport services and electronic components industries have been identified as sectors which could have labour supply issues during peak employment of the SBSP programme. There is a risk that the goods and services from these sectors to deliver SBSP will need to be imported without a significant investment in skills and education to increase the domestic supply of labour in these two sectors.

6. **There are broader economic benefits for the UK to pursue the development of SBSP.** A UK-based SBSP system could support a significant economic footprint. The GDP contribution of the 50^{th} percentile of programme costs is estimated at £6bn in 2018 net present value terms (based on cost estimates excluding optimism bias)—a GDP multiplier of 2.3. The benefit-cost ratio of private sector returns on a first of kind SBSP system receiving public funding is estimated at 1.9:1. In addition the development programme is expected to lead to advances in technology that will create spill-over benefits. Notably, wireless power transmission, autonomous robotic assembly, and market opportunity for space freight transportation.

7. **The UK is well positioned to lead the development of SBSP from a number of perspectives.** SBSP appears to be well aligned with existing UK Government strategies and priorities and the UK has strong research, technical, industrial and regulatory capabilities in relevant areas to capitalise on.

8. **There are many development risks and issues associated with a SBSP system.** Whilst the findings of this economic feasibility study are generally positive, there are a number of significant challenges and questions that need to be answered which could be addressed by parallel studies and demonstration activities.

7.2 RECOMMENDATIONS

The main recommendations are grouped in five areas:

1. Policy and Strategy
   - Use existing energy models to quantify the contribution that SBSP could make to the UK energy mix;
   - Consider the integration of SBSP across relevant Government strategy and policies, including Net Zero; National Space Strategy; Innovation Strategy;
2. UK Research and Development
   - Conduct concept design studies to derive a set of user and system requirements, together with an operational concept, a programme management plan, and a risk and opportunity management plan;
   - Examine those issues beyond the scope of this study, including the political, societal, legal and environmental considerations for SBSP;
   - Establish a multi-year programme of technology development to address high risk and low maturity areas;
   - Establish the SBSP industrial and technology priorities for the UK, to help industry plan and to position the government for international discussions;
3. Energy market engagement
   - Engage further with the energy generation and distribution companies as key future stakeholders.
   - Maintain technology watch on the development of other renewable energy options, to evaluate whether SBSP remains competitive and affordable in the energy market.
4. Space Transportation
   - Conduct regular analysis of international market trends and capabilities to inform strategic decisions on procuring space lift;
   - Establish UK strategy for collaborative development or procurement of fully reusable heavy lift capability;
   - Together with European partners, explore the business case and development path for the UK's SABRE air breathing engine technology as a core component of a future European fully reusable heavy lift launch system;
5. International collaboration
   - Consider profiling SBSP at the COP26 conference in November 2021, as a platform for testing public opinion, signalling policy and starting international dialogue.
   - Given a clear view on UK R&D priorities, initiate international discussions with the 5 Eyes Nations plus Japan to explore collaboration on a development programme;
   - Commence initial discussions, perhaps as part of an international consortium, with the International Telecommunications Union on spectrum allocation for SBSP;
6. 'No regret' research
   - Consider establishing a SBSP development programme. A number of spill-over benefits which may result from research activities carried out during the development phases are identified that have wider application and value to the UK economy. Therefore, the initial stages of the development programme presents a 'no regret' research path that would deliver value irrespective of an operational SBSP being realised.

8. REFERENCES

[1] S. Way and J. Lamyman, “Space Based Solar Power as a Contributor to Net Zero Phase 1: Engineering Feasibility Rep,” Frazer-Nash Consulancy, FNC 004456/51057R, 2020.

[2] HM Treasury, “GDP deflators at market prices, and money GDP March 2020 (Budget),” GOV.UK, 2020.

[3] OFX, “Yearly Average Rates,” 2020. [Online]. Available: https://www.ofx.com/en-gb/forex-news/historical-exchange-rates/yearly-average-rates/. [Accessed 02 02 2021].

[4] Office of National Statistics, “Annual Business Survey - 2018 Provisional Results; Standard Extracts,” 2019.

[5] S. Shapiro, “Operators go uninsured due to cost and in-orbit coverage limitations,” 2007. [Online]. Available: https://www.businessinsurance.com/article/20070422/ISSUE01/100021660/operators-go-uninsured-due-to-cost-and-in-orbit-coverage-limitations. [Accessed 01 02 2021].

[6] “https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/employmentandemployeetypes/datasets/industry235digitsicbusinessregisterandemploymentsurveybrestable2,” [Online].

[7] J. R. Wertz and W. Larson, Space Mission Analysis and Design, 1999.

[8] J. Linick, “Technology Readiness Level (TRL) vs. Percent Development Cost,” in *ICEAA Professional Development & Training Workshop*, 2017.

[9] HM Treasury, “The Green Book: Appraisal and Evaluation in Central Government,” GOV.UK, 2020.

[10] I. Sobol, “Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates,” [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0378475400002706?via%3Dihub.

[11] J. Mankins, “SPS-ALPHA: The First Practical Solar Power Satellite via Arbitrarily Large Phased Array,” NASA, 2012.

[12] I. Cash, “CASSIOPeiA - A new paradigm for space solar power,” *Acta Astronautica,* vol. 159, pp. 170-178, 2019.

[13] Department for Business, Energy and Industrial Strategy, “Electricity Generation Costs,” GOV.UK, 2020.

[14] London Economics, “Spillovers in the Space Sector,” 2018.

[15] Frontier Economics, “Rates of return to investment in science and innovation,” Department For Business, Innovation and Skills, 2014.

[16] B. Preston, “Plowshares and Power: The Military Use of Civil Space,” Natl Defence Univ Pr, 1994.

[17] Department of Energy & Climate Change, “https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/263937/Final_Document_-_Investing_in_renewable_technologies_-_CfD_contract_terms_and_strike_prices_UPDATED_6_DEC.pdf,” 2013.

[18] C. T. Rodenbeck, P. I. Jaffe and e. al, “Microwave and Millimeter Wave Power Beaming,” *IEEE Journal of Microwaves,* 2021.

[19] “Single Departmental Plan,” [Online]. Available: https://www.gov.uk/government/publications/department-for-business-energy-and-industrial-strategy-single-departmental-plan/department-for-business-energy-and-industrial-strategy-single-departmental-plan-june-2019#deliver-an-ambitious-industrial-strategy.

[20] “Satellites to be Built and Launched by 2028,” Euroconsult, 2019.

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