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Study on Cost-Benefit Analysis of Space-Based Solar Power (SBSP) Generation for Terrestrial Energy Needs

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Study on Cost-Benefit Analysis of Space-Based Solar Power (SBSP) Generation for Terrestrial Energy Needs

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1 Introduction

The European Space Agency (ESA) commissioned Frazer-Nash Consultancy (Frazer-Nash), in partnership with London Economics to carry out a study on cost-benefit analysis of space-based solar power generation (SBSP) for terrestrial needs.

The study aimed to provide a holistic assessment of the required investments, associated costs and risks and expected strategic, environmental, economic and societal benefits of adding this space-based energy source to the European energy mix to meet Net Zero carbon by 2050. The study used CASSIOPeiA—a SBSP satellite designed by International Electric Company (IECL)— as its reference design architecture.

This report is the final report generated as part of the study. It provides a description of the activities carried out and details the main study results. The study generated five technical notes (TN) which inform the results presented in this report. They are:

- **TN1** - Review of previous SBSP studies and identification of limitations and gaps. [1]
- **TN2** – Methodological approach to be use in Task 3 for the assessment of strategic, economic, environmental, and societal benefits, costs and risks. [2]
- **TN3** – System Breakdown, Costs and Technical Feasibility. [3]
- **TN4** – Assessment of strategic, economic, environmental, and societal benefits, costs and risks. [4]
- **TN5** – Concept for a European SBSP Development Programme. [5]

A parallel study was commissioned by ESA to consider the same topic but focusing on a different SBSP architecture. This parallel study, carried out by a partnership of Roland Berger and OHB was entirely independent to the study presented in this report.

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 to date been considered by European governments.

Recent advances in system concepts, maturing technology, changes in the energy market, and a dramatic fall in the cost of space launch have made SBSP a more viable concept, both technically and commercially. To meet the growing European energy demands and to support climate neutrality in Europe, ESA would like to reconsider the potential of SBSP, a concept which it first considered 15 years ago.

1.2 Report Structure

The report is arranged into three chapters.

- **Chapter 1** – this introduction, sets the scene for the report
- **Chapter 2** describes the study methodology
- **Chapter 3** presents the key findings

2 Programme of Work

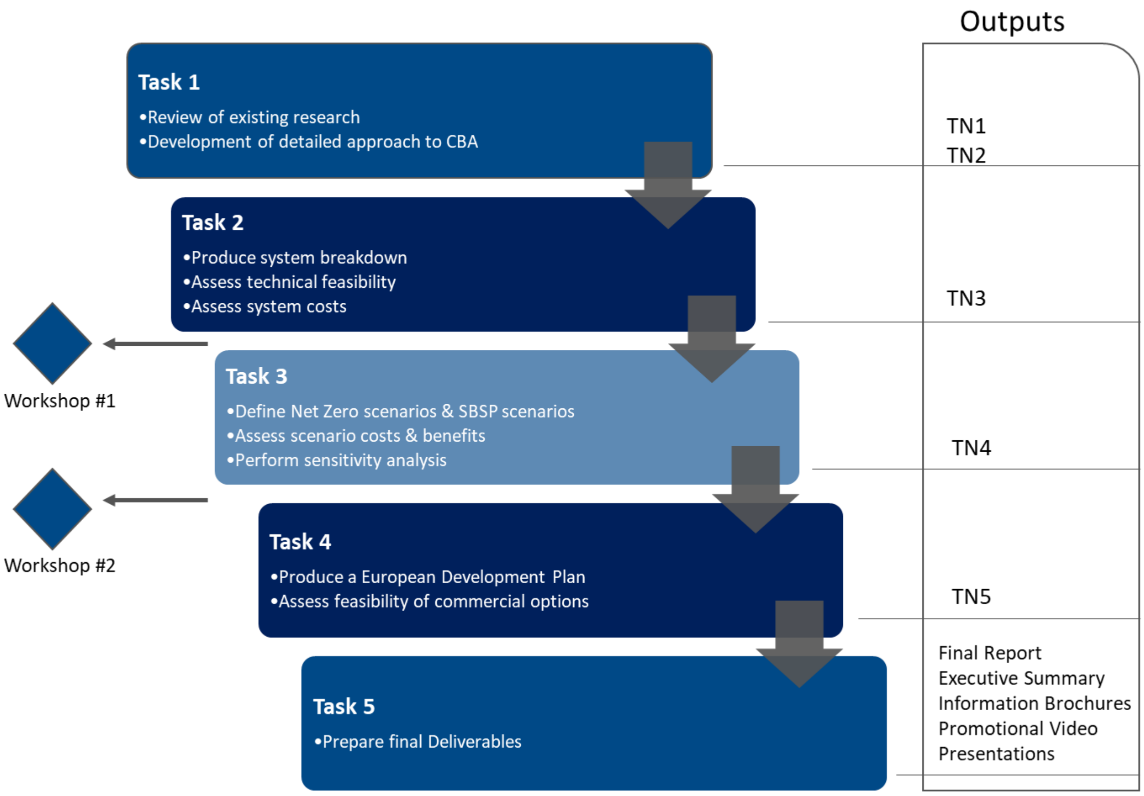
2.1 Study Activity

The study comprised five key tasks:

- **Task 1** – a review of previous studies and proposed methodological approach
- **Task 2** – a technical feasibility assessment of costs to include a system breakdown of the CASSEOPeiA design
- **Task 3** – an assessment of the strategic, economic, environmental and societal benefits, costs and risks.
- **Task 4** – the development of a concept development programme for a European SBSP and associated commercialisation options.
- **Task 5** – the preparation of final study outputs.

In addition, there was an initial series of project mobilisation activities to initiate the study. The tasks were fundamentally delivered sequentially, overlapping where possible so that the study could be delivered within a six-month period. Two stakeholder workshops were delivered at key stages of the study, to gather intelligence and sense-check emerging findings. Around 40 individuals representing 18 organisations from across government, industry and academia took part in the workshops. A list of companies engaged through the workshops can be found in Annex A.1. Figure 2-1 presents an overview of the programme of work.

Figure 2-1 High-Level Overview of Project Activities and Study Outputs



A detailed description of the methodology undertaken for each task follows.

2.2 Methodology

2.2.1 Task 1

Task 1 comprised desk-based research of existing published information leading to a written literature review (TN1) [1], followed by the development of a detailed methodology for the cost-benefit analysis that would be carried out in Task 3 (TN2) [2]. A list of research papers reviewed can be found in Annex A.4. This critical review involved an initial rapid-evidence assessment of the listed reference documents to enable categorisation of the documents to direct the focus of the review. A subsequent thorough review was carried out to address the literature review objectives in more detail. The aim of the review involved answering the following research questions that underpin the evidence and knowledge needed to provide a comprehensive study of SBSP in the European energy pathways.

What motivates interest in an alternative energy source?

What is Net Zero and what are the pathways for Europe to getting there?

What is the energy outlook for the five countries?

What is the current understanding of the technical feasibility of an SBSP system?

What are the leading Solar Power Satellite concepts, and which is worth consideration as the reference case?

What are other benefits of the SBPS – strategic, security, resilience, potentially economic, other benefits?

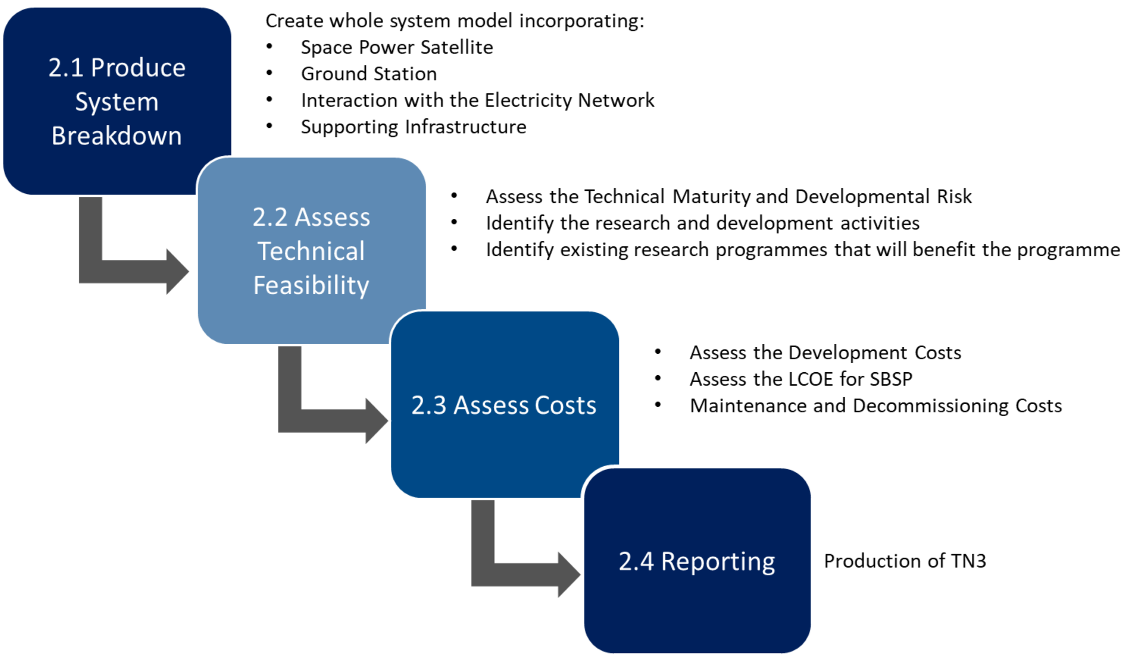
What are the current gaps in our understanding of the SBSP concept?

What key considerations are there for the cost-benefit analysis of SBSP?

2.2.2 Task 2

The objective of this task was to assess the technical feasibility of GW scale SBSP development by 2040. This assessment was based on a CASSEOPeiA reference design. It identified the required technologies and the associated development, implementation, and maintenance costs to deploy a first European GW-level Solar Power Satellite by around 2040. An overview of the approach is presented in Figure 2-2, and a detailed description follows.

Figure 2-2 Task 2 - Methodology overview



- **System Breakdown** – a system breakdown was developed, by building on an existing generic breakdown created as part of a separate study [7] carried out for the UK Government Department (BEIS[1]). The breakdown included both the space power satellite (SPS), and ground station and its interaction with the electricity network. The generic breakdown was modified to include specific considerations for a CASSEOPeiA reference design.
- **Assessing Technical Feasibility** – to understand the technical feasibility each constituent system element as detailed in the breakdown was explored by reviewing existing publications, including justification from analogous technologies or industries, and sense-checking through independent subject matter expert scrutiny. The emerging findings were scrutinised further at a key stakeholder workshop (see Section 2.2.3). For each technology the following factors were considered:
  - the technical maturity and associated development risk by assessing its Technology Readiness Level (TRL) and considering development difficulty.
  - the research and development activities which will be required to meet the level of technology needed. This included the identification of significant engineering barriers to overcome in order to mature each of system elements and mitigate the technical risk.
  - existing development and research programmes which are developing technologies in areas which may benefit a SBSP development programme.
- **Assessing Costs** – to assess the system costs the existing SBSP cost model which Frazer-Nash developed for a previous study [2] was used. The model was adapted to consider additional factors where new data or insight enabled refinement to the model structure. The model defines all known factors which influence system cost and defines dependency relationships between these factors. Cost estimates were calculated using probabilistic mathematics, based on ranges of input variables. The input ranges are based on published information where possible, or else expert judgement. The values were scrutinised at the study workshops (see Section 2.2.3). Further details about the model structure, inputs and outputs can be found in Technical Note TN3. [3]. A list of Capex and Opex cost assumptions is presented in Annex A.1. Annex A.2 details the approach to estimating development costs.
- **Producing Report** – the findings were compiled into a technical note (TN3) [3]

2.2.3 Workshops

A series of two stakeholder engagement workshops were delivered to feed into tasks 2,3 and 4. The workshops were attended by more than forty individuals representing eighteen organisations as listed in Annex A.1. Each workshop was delivered virtually using Microsoft Teams, and each followed a prescribed set of topics as shown in Table 2-1. The workshops utilised interactive questioning and breakout rooms to maximise attendee participation. Workshop outputs were shared with attendees after each workshop.

The first workshop took place on 25th March 2022 and focussed on discussions regarding the energy and technical systems separately. This workshop was jointly delivered by both the Frazer-Nash and Roland Berger led study consortiums delivering parallel but independent studies. The second workshop was delivered solely by the Frazer-Nash led partnership, to ensure that emerging findings from each study did not influence the other. This workshop, which focussed on discussing the emerging outputs from the cost-benefit analysis and development pathway was held on the 6th May 2022.

[1] The Department for Business, Energy and Industrial Strategy

Table 2-1 Workshop Aims & Topics

Workshop #1	Workshop #2
Aims ‣ Consider the strategic, economic, societal and environmental costs and benefits of introducing SBSP capability into Europe's energy generation portfolio ‣ Explore the perceived technical and political barriers to development with the stakeholder community ‣ Discuss net zero scenarios and the challenges facing European countries ‣ Explore the viability and technical feasibility of SBSP systems ‣ Understand the potential economic benefits, the system cost and commercialization options	**Aims** ‣ Discussion on SBSP system scale, costs and development timeline ‣ Explore the potential economic, societal and environmental value of introducing SBSP capability into Europe's energy generation portfolio ‣ Consider suitable Commercialisation options for the development of a first (and subsequent) European SBSP system
Topics ‣ Energy System – Net Zero context – Wider benefits of SBSP – Commercial models ‣ Technical System – System breakdown, technical feasibility – System cost assumptions	**Topics** ‣ SBSP System ‣ SBSP in the European Energy Mix ‣ Commercialisation Options

2.2.4 Task 3

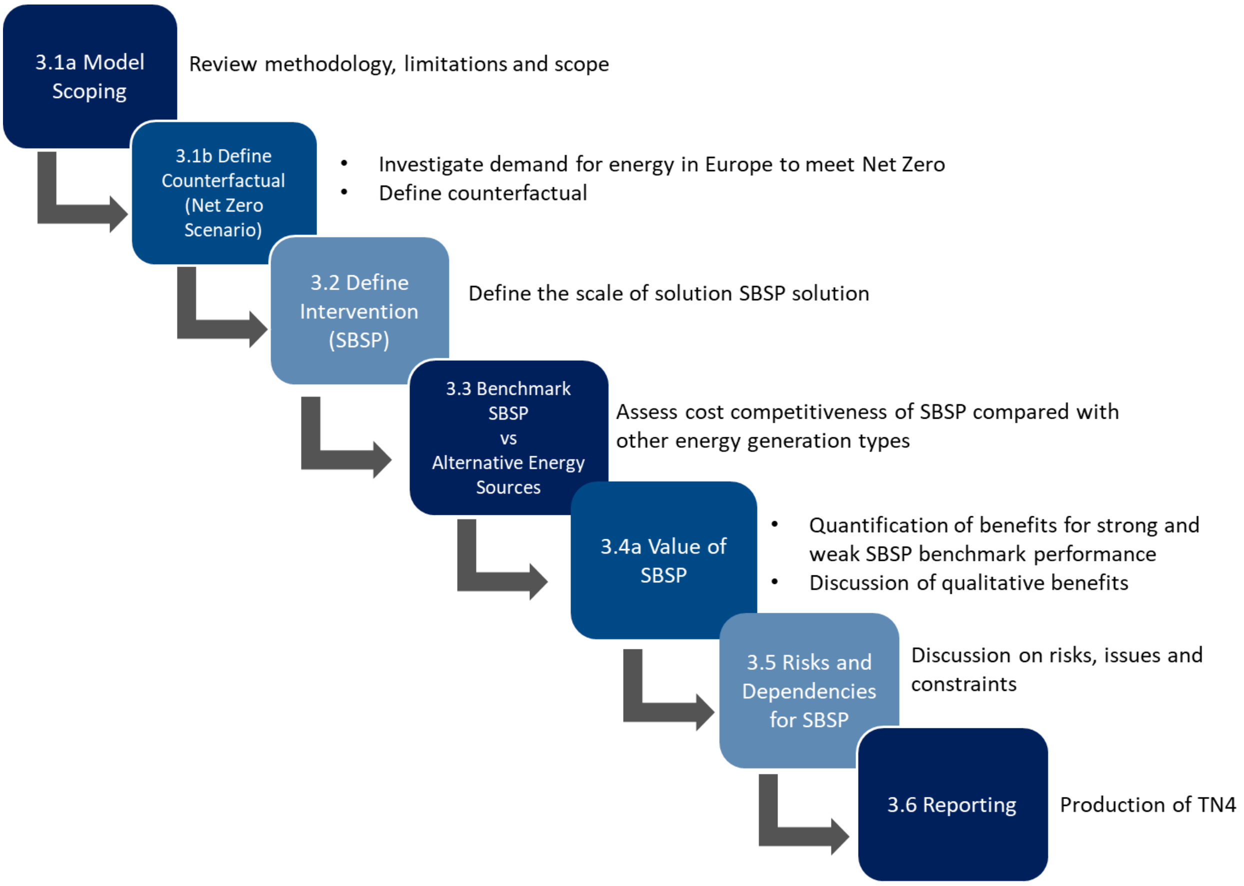
The aim of Task 3 was to assess the benefits, costs, and risks associated with a potential European SBSP capability for terrestrial energy needs, including the impact of SBSP on Europe's energy supply and climate change efforts. A 'social value' approach was taken which allows for monetisation of benefits (economic, strategic, environmental, social) that can be expected from the European SBSP capability versus the costs for implementing it relative to a counterfactual—where there is no SBSP capability in Europe.

This approach approach is popular with governments, investors and other stakeholders to appraise the desirability of a given investment, program or project and make comparisons with different options. This is because it ensures:

- accountability and transparency because it clarifies which costs and benefits are accounted for, and
- provides decision makers with an investment rationale.

Additional costs and benefits that cannot be monetised were identified and qualitatively assessed. A detailed description of the approach to Task 3 can be found in TN2 [2], a diagrammatic overview is presented in Figure 2-3, and a summary of each stage is detailed thereafter.

Figure 2-3 Task 3 – Methodology Overview



- **Task 3.1a Net Zero Scoping** - the methodology, limitations and scope were reviewed as part of Task 1, resulting in the production of TN2.
- **Task 3.1b: Net Zero Scenarios (counterfactual) –** established a 'counterfactual' (i.e. what would have happened in a future without SBSP), over the time period of analysis, by investigating how demand for energy is expected to evolve in Europe, and what energy generation sources are expected will meet the demand. This resulted in the formulation of two scenarios (the Net Zero, and the Business as Usual), which capture the inherent uncertainty in predicting the future. The benefits of SBSP are assessed against this counterfactual.
- **Task 3.2: Define SBSP scenario (intervention)** – defined the scale of SBSP solution including the technical specification, a theoretical maximum contribution, and viable system scale(s), and costs.
- **Tasks 3.3: Benchmarking** – assessed the cost competitiveness of SBSP compared with alternative energy generation types, considering both the levelised cost of electricity (LCOE) and the more holistic value-added LCOE (VALCOE). The difference between VALCOE and LCOE was integral to the benchmarking of SBSP as a marginal energy source because it enables an assessment of the extent to which SBSP can displace alternatives.
- **Task 4: Valuing benefits** – the benefits of SBSP – comprising strategic, economic, environmental, and societal benefits – were quantified where possible and evaluated qualitatively where they could not be quantified.
- **Task 5: Risk / dependencies** – any risks or dependencies that could impact upon the success of SBSP were identified and discussed.
- **Task 6: Reporting -** the findings were compiled into a technical note (TN4) [4] and accompanying country-level analysis (TN4.1 [7]).

The approach described above is subject to significant uncertainties owing to the long timeframe of analysis and the relative technical immaturity of the SBSP concept. Annex A.5 provides a detailed account of the assumptions, caveats and limitations to the methodology discussed here. A summary of these is presented in Table 2-2

Table 2-2 Cost-benefit Methodology Assumptions, Caveats and Limitations – Summary Table

Assumption	Detail
Counterfactual Scenario	The study assumes that development of a European SBSP concept is only achieved through a single pathway – i.e., that a European SBSP will not be developed without public sector intervention.
Change	Differences in the SBSP specification will alter both the cost of the system and, on the benefits side, the amount of energy supplied (and avoided carbon etc) that can be addressed by the SBSP system and therefore the benefit and costs that can be achieved.
Time Period	For the development phase a starting date of 2022 through to 2040 is assumed. This is suggested because a previous study (UK BEIS [6]) noted a ~20-year development programme (including 2020), of which it allowed for a 2-year construction schedule per satellite. This assumption implies full operational capability (FOC) of the system by 2040
Geography	Once operational, it is assumed that the European SBSP capability will be able to transmit energy across Europe. This assumes that the space segment of the system will exist at a fixed point in GEO with full coverage of Europe and that the ground segment, including rectennas for receiving transmitted energy, will be constrained to Europe.[2]
Technical Feasibility	The technical feasibility is based on assumed performance parameters as set out in TN3 [3] and referred to in Chapter 0 of this report.
Stakeholders	Two stakeholder groups are defined: **Cost-bearers** – Procurers of the SBSP capability, operators of the SBSP capability and electricity system operators **Beneficiaries** - European energy users, European states, and European industry and citizens more broadly as users and economic/strategic/environmental beneficiaries of the European SBSP capability
Benefits	Benefits are analysed against the counterfactual, or reference, scenario, i.e., the scenario that would occur in the absence of the construction of SBSP satellites and associated ground infrastructure.
Costs	Cost estimates are defined in TN3 [3]. The costs used in this analysis uses a Europe average for the first of a kind (FOAK), and then adjusts this to account for learning rates and economies of scale to derive a 10th of a kind.
Discount Rates	Two discount rates are assumed: **Social discount rate:** a rate of 3.0% as suggested by the European Commission is used to discount future cost and revenue estimates to a present value, which is required for a fair comparison with alternatives. **Discount rate for LCOE:** a discount rate is used to account for the costs of capital and risks in the project. It is based on the projected hurdle rate[3] required by institutional investors, which

[2] Europe is defined by the 'seven continents' definition of Europe, comprising an area of 10.18 million km2 or 2% of the Earth's surface, and 50 sovereign states.
[3] A risk-adjusted cost of capital.

Assumption	Detail
	reflects the high uncertainty due to the long-time horizon and technical development that is required. To reflect this, a risk-adjusted discount range of 20% for SBSP has been chosen for this study. The impact of varying the hurdle rate is considered where appropriate.
Caveats & Limitations	Description
Estimating	Benefits are estimated for a new technology operating within a fast-changing energy market over a long timeframe many decades into the future. Best judgement and research have been used to identify reasonable assumptions for the counterfactual scenario and of the context in which SBSP will operate. However, these factors are subject to a high degree of uncertainty. To manage this, assumptions are documented, known uncertainties are identified, and multiple sensitivities are modelled.
Quantifying qualitative factors	Selective attempts have been made to quantify variables that can be best defined qualitatively. The detail and nuance present in the narrative should be studied by decision makers as closely as the quantitative benefit estimates themselves.
Government Policy	The funder / owner / operator of the first of a kind will ultimately be the arbitrator of all strategic decisions on the design, scaling, targeting and commercial model of the system. All of these factors will affect the costs and benefits. Sensitivity adjustments have been used to infer the impact of various decisions, but decision makers should make their own judgements on the information presented.
System uncertainty	Large scale infrastructure projects, including in space, have a history of cost and time overruns as frontier projects need to solve problems that are unknown at the outset. This report is based on best estimates on time and costs and tend towards conservative estimates when in doubt
Energy Landscape	There is a non-negligible chance that a competing technology will reach maturity during the course of SBSP development, thus changing the landscape SBSP will enter.
Uncertain forecasts	The forecasted demand is based on published sources but due to inherent uncertainty in forecasting, these may not be accurate.
LCOE uncertainty	The LCOE estimate relies on many assumptions which cannot be verified this far in advance. The analysis therefore represents a best estimate of the situation as will arise in the future, but the results should be interpreted with caution.

2.2.5 Task 4

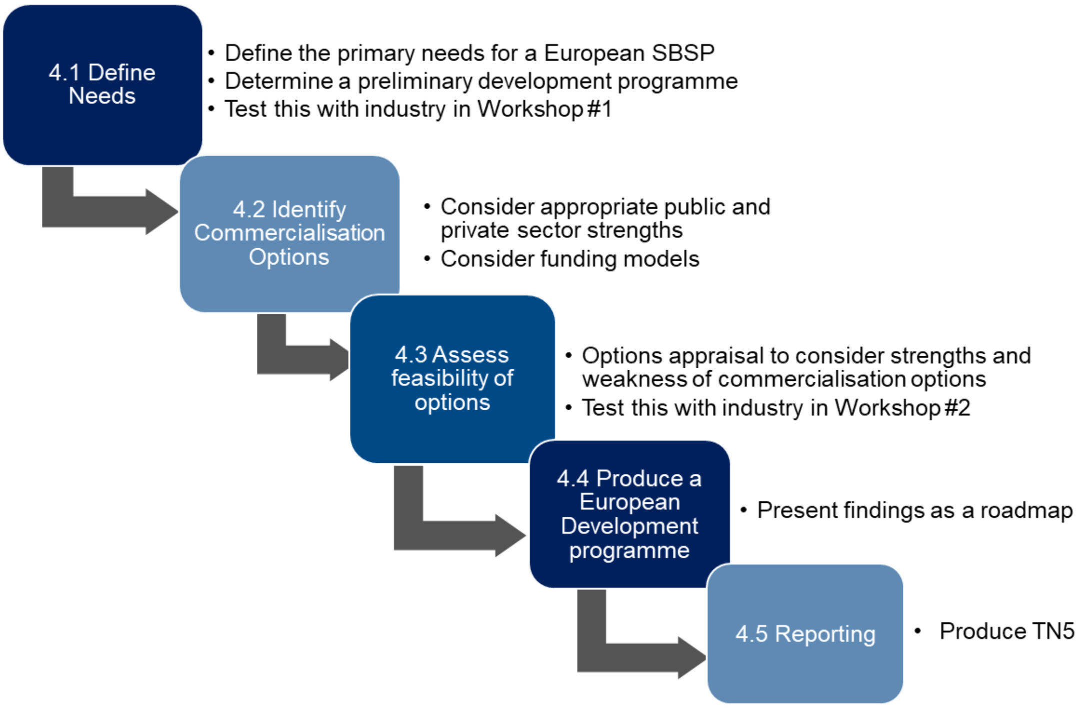
The aim of Task 4 was to create a European SPS development pathway and consider commercialisation options for delivery of the programme. The approach taken was to build on the technical feasibility and cost assessment presented in TN3 [3], and the SBSP solution scale presented in TN4 [4], to document a route from concept to first European SBSP capability.

The activity was geared towards answering the question:

- What information do decision makers need to be able to fully assess the commercialisation routes to achieving a viable European SBSP?

To answer the questions the study produced two discrete elements. Firstly, a realistic development programme was produced, with key milestones that if achieved, would breed sufficient confidence that SBSP can become a reality. Secondly, based on such a programme, an assessment of suitable commercialisation options that make it a financially and economically viable solution were undertaken. The initial development plan and commercialisation options were introduced at the first key stakeholder workshop to test their viability. Through a combination of desk-based research and engaging with the stakeholder community, existing evidence relating to both an SBSP programme (and comparable systems where appropriate), and commercialisation options were scrutinised by the study research team. This information was reviewed again at the second workshop. TN5 documents detailed outputs of this study and Chapters 3.5 and 3.7 detail the key findings.

Figure 2-4 Task 4 – Methodology Overview



2.2.6 Task 5

The final task included the production of a final set of study outputs as follows:

- This report – which provide a description of the study programme and key findings
- An executive summary that summarises the study key findings
- A promotional brochure which has been produced to raise awareness of the study concept and findings
- A promotion video to accompany the brochure and provide high-level contextual information.

3 Results – Technical Feasibility, Costs and Benefits

3.1 Literature Review: Gaps in existing knowledge and limitations of previous studies

The literature review set out to synthesise all known existing research papers related to the topic of SBSP to shed light on the research questions set out in Chapter 2.2.1 of this report. The review concluded several gaps and limitations of current understanding of SBSP. They are noted below:

Net Zero transformation

- Published pathways to Net Zero are aspirational, and none consider how achievable they are, or the practical steps to deliver the pathways.
- There is no analysis of the dis-benefit of a future with more expensive, more unreliable energy if we do not pursue SBSP.
- There is no study of the scale of SBSP that be optimal within a clean energy mix, and what that might mean for the other energy technologies.
- There is little discussion of the societal or political challenges and factors for success in introducing a new disruptive energy technology which could transform our clean energy future.

Economics and finance

- Economic analysis of SBSP has tended to focus rather narrowly on the LCOE, rather than the wider holistic benefits that SBSP could bring in helping to de-risk Net Zero, its value integrating into a whole energy system, as well as its impact on the space economy.
- Many of the reference documents are a decade or more in age, and the technology and economics have transformed during that period. Some of the conclusions drawn—especially on economics—are therefore no longer valid.
- Limited consideration has been given to models for a combined public and private finance model for a development programme, notably one that bridges the technological and commercialisation 'valley of death'.
- There is limited information (2 references) on the sensitivity of LCOE to parameters such as the cost of money, development timescales, launch, specific power, and future regulations.

Development risks

- There has been little or no differentiation between the core technology which is bespoke and must be developed as part of an SBSP programme, and the enabling technology that are assumed to be developed elsewhere. Examples of the latter include the space launch capacity, photovoltaic technology, and assembly robotic systems.
- Aside from the need for radio frequency (RF) spectrum allocation, there is limited discussion of the wider legal and regulatory issues, many of which will need international agreement to develop and deploy these systems in a responsible and sustainable way.
- There is no detailed analysis, beyond a superficial discussion, of the technical, environmental and wider risks that need to be addressed during a development programme.

Market and Supply Chain

- There is no market analysis of how the different energy network operators (generators, utilities, transmission and distribution companies) might own and operate parts of a future SBSP system.

- There has been no documented engagement with the space launch sector to explore the practical challenges of radically increasing launch capacity, reliability, tempo and affordability, whilst at the same time moving to fully sustainable fuels.

3.1.1 Literature Review Recommendations

TN1 concluded that there is an opportunity to further our understanding of the technical and economic aspects of SBSP in a Net Zero context during this study. As a result, it postulated the following recommend actions that should be incorporated into this research.

1. Use a system value framework for assessment of broader benefits for SBSP, including economic, political, societal, industrial, health and well-being, international collaboration, security, inspiring the next generation into STEM[4], and enabling the growth of new markets and industries.
2. Perform a cost benefit analysis using a selected system concept, and base this in the physics of SBSP which translates into the key metrics (mass, efficiency, cost etc).
3. Undertake a comparison with existing energy technologies and assess a broad range of both quantitative and qualitative criteria.
4. Identify the different constraints on individual European countries, such as nuclear power policy, land / coastal area for rectenna placement.
5. Look at investable public / private financing models which will see patient capital support a development through to TRL 8.
6. Illustrate the system and subsystems in simple, well-crafted visual designs / flow processes to show the key metrics, dependencies, and variables.
7. Make the analysis, assumptions, uncertainties and data clear and transparent, and present the findings in a highly accessible way. This will help others to independently peer review the work so that trust is built with stakeholders.
8. Develop a stakeholder map and align the messaging with key stakeholders.

3.2 Technical Feasibility

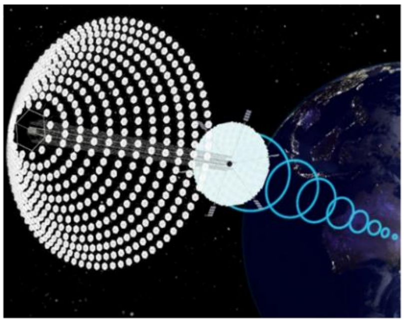
3.2.1 SBSP Concepts

A typical SBSP system concept comprises a massive, kilometre-scale satellite in a geostationary orbit (GEO), at 35,786 km above a point on the Earth for GW scale generation. At this altitude the Sun is visible over 99% of the time, with short predictable periods in the spring and autumn totalling 82 hours per year where the satellite is in the Earth's shadow. A secure pilot beam is transmitted from the ground to the satellite to allow the microwave beam to lock onto the correct target. The rectenna converts the electromagnetic energy into direct current electricity which is converted and transformed to provide power to the grid with acceptable characteristics. Theoretically therefore, a SBSP can provide almost continuous base load power all year round.

[4] Science, Technology, Engineering and Maths.

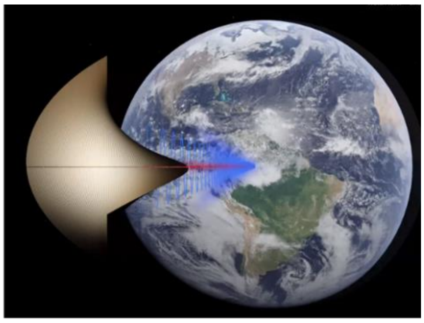
There are three leading designs globally, which solve the rotational mismatch issue caused by the need to be pointing to both the sun and a fixed point on earth, during orbit. They are shown in Figure 3-1. A diagram to illustrate scale of the CASSIOPeiA design is offered in Figure 3-2.

Figure 3-1 Three leading solar power satellite concepts capable of providing baseload power



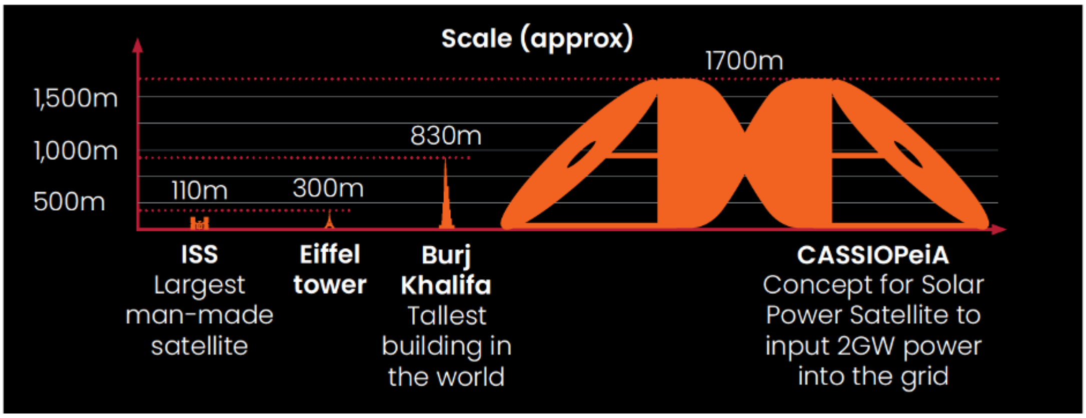
SPS Alpha
John Mankins, USA

Multi-Rotating Joints SPS
Xinbin Hou, CAST, China



CASSIOPeiA
Ian Cash, IECL, UK

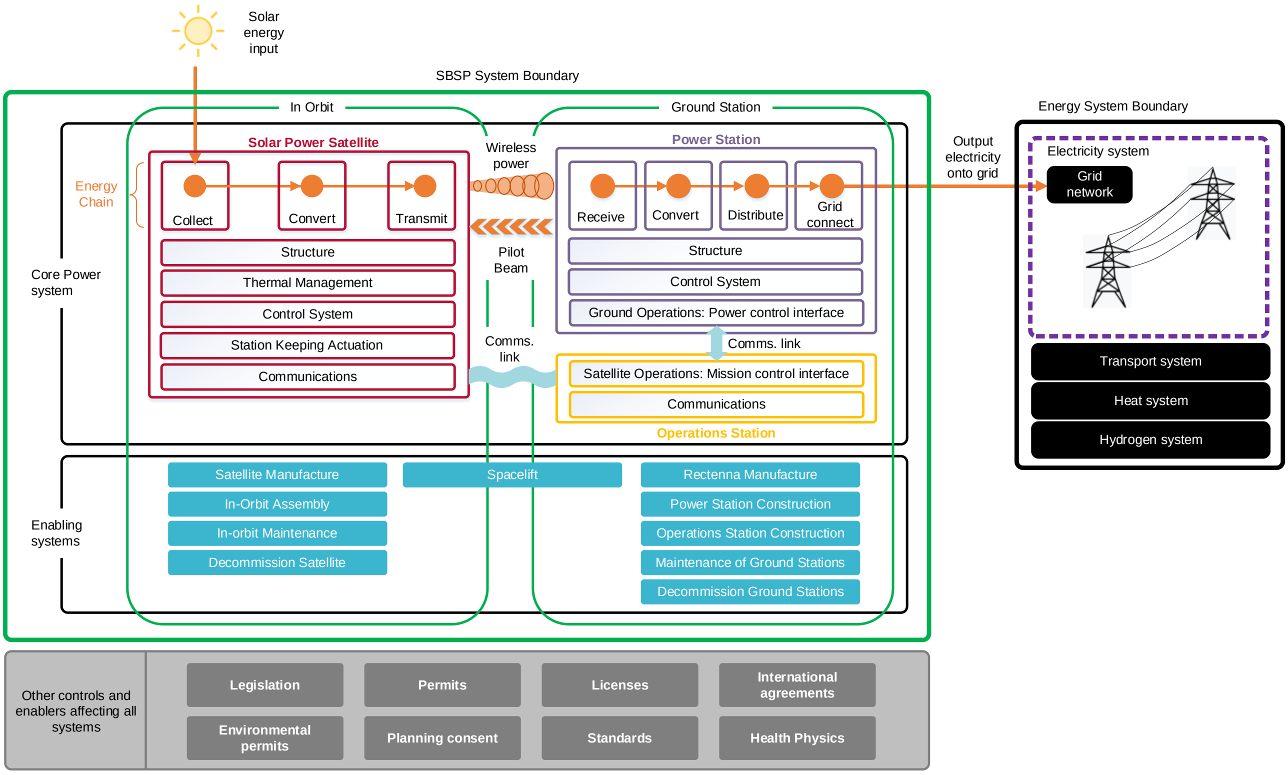
Figure 3-2 Relative Scale of CASSIOPeiA reference architecture



3.2.2 SBSP System Overview

The system breakdown describes the functional element of the system and provides a framework for this technical feasibility assessment. The system breakdown for a generic grid connected SBSP system is illustrated in Figure 3-3. The system boundary of an operational system is illustrated by the thick green line. It is recognised that there are other factors, apart from the technical elements, that will affect the operation of the system. Some of these are illustrated in the grey box at the bottom of Figure 3-3. A summary overview of the characteristics of CASSIOPeiA is provided in the following sub-section. Technical Note TN3 [3] provides further details.

Figure 3-3 System Breakdown



3.2.2.1 Solar Power Satellite

The focus of the technical feasibility assessment was the CASSEOPeiA reference SBSP architecture. A CASSIOPeiA solar power satellite incorporates an electronically steered microwave beam that removes the need for any mechanical elements and allows all the elements to be utilised continuously; all the photovoltaic (PV) elements receive constant insolation and all the radio frequency (RF) elements are active throughout the orbit.

CASSIOPeiA uses a novel three-dimensional phased array antenna for the RF transmission, integrated with a helical photovoltaic collector. The PV cells within the helical array are positioned edge-on to the sun. Mirrors positioned at either end of the helical array axis point at the sun and direct the incoming insolation along the axis of the helical array onto the PV cells. The concept is able to employ a variety of PV technologies, however it is likely that high concentration PV will provide the highest performance.

The novel aspects of CASSIOPeiA are described in the Patent GB2563574 [9]. The general arrangement of the concept is presented in various papers [10] and conference presentations such as International Space Development Conference [11] and IEE Wireless for Space and Extreme Environments [12].

There are a number of different implementations of the CASSIOPeiA concept. The largest practical size of a single CASSIOPeiA solar power satellite in a geostationary orbit uses the patented Solid State Symmetrical Concentrator [13] that can generate 2 GW into the grid. However, for this study we consider a slightly simpler implementation of CASSIOPeiA, illustrated in The core of the satellite is a 2 km diameter helical array with 61,000 layers (the illustration in Figure 3-4 presents a simplified view of the layers). This collects the solar radiation from the pair of angled mirrors at each end of the satellite and uses photovoltaic cells to generate electricity which power the microwave transmitters. The architecture of CASSIOPeiA does not restrict the type of photovoltaic technology that could be used. However, for this study it is assumed that the system will use triple junction space rated high concentration photovoltaic cells with Fresnel primary optics and Köhler secondary optics . The microwave beam is generated by triple dipole antennas on the vertical walls of the helical array. These operate at 2.45 GHz and use the pilot beam received from the ground station to provide a reference for the microwave beam. The peak intensity of the microwave beam at the centre of the rectenna on the ground is 245 W/m^2. Each system generates 1.44 GW of electrical power into the grid.

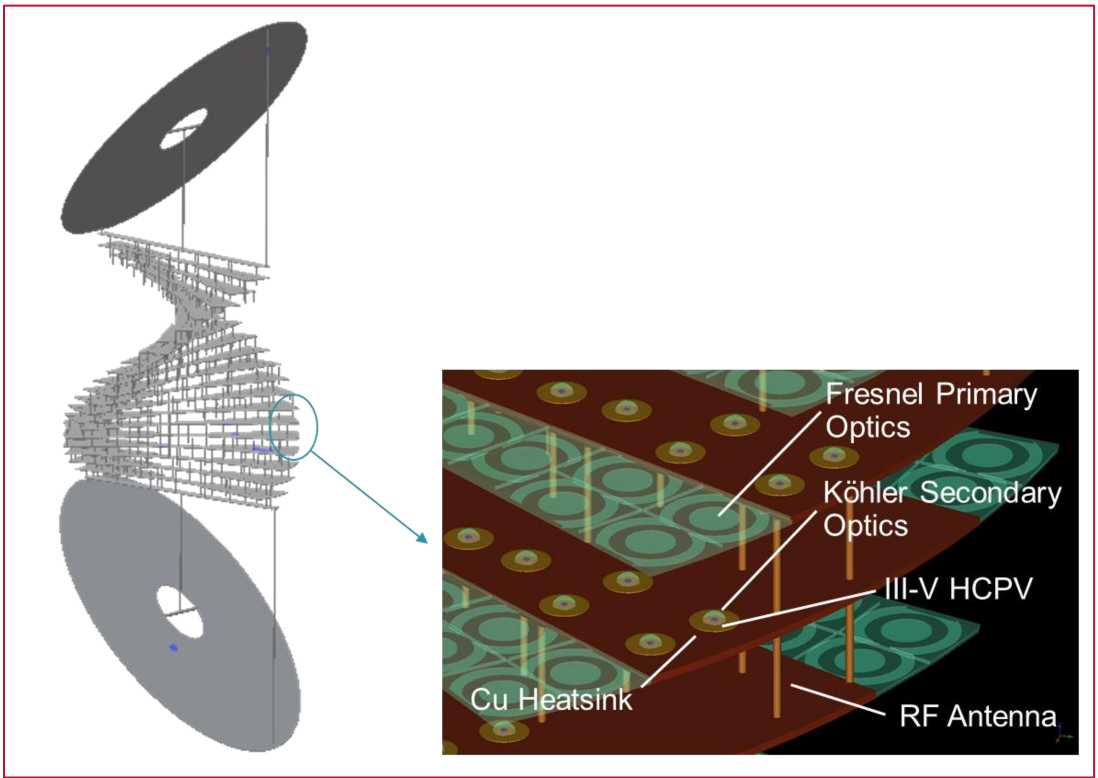
The design of a SBSP system is a balance between a number of competing factors; minimising the size of the satellite whilst limiting the thermal load on the PV to optimise their efficiency and limiting the maximum microwave intensity at the ground. For the purpose of this investigation the typical mass breakdown of the key elements of the satellite is detailed in Table 3-1

Table 3-1 Typical Satellite Mass Breakdown for 1.44 GW system

Satellite Sub System	Mass (kg)
PV	1,349,200
Reflector	158,600
Wireless Power Transmission	358,400
Thrusters	2,100
Communications and Control	9,500
Structure	186,400
Total	**2,064,200**

that is better suited to an initial system implementation as it provides a better balance between development risk and performance. The image also gives an indication of the design maturity of the concept and hence the level of fidelity available to inform this study. Where design detail has yet to be developed, we have had to make bounding assumptions.

Figure 3-4 Skeleton Sketch of CASSEOPeiA Concept



The core of the satellite is a 2 km diameter helical array with 61,000 layers (the illustration in Figure 3-4 presents a simplified view of the layers). This collects the solar radiation from the pair of angled mirrors at each end of the satellite and uses photovoltaic cells to generate electricity which power the microwave transmitters. The architecture of CASSIOPeiA does not restrict the type of photovoltaic technology that could be used. However, for this study it is assumed that the system will use triple junction space rated high concentration photovoltaic cells with Fresnel primary optics and Köhler secondary optics [14]. The microwave beam is generated by triple dipole antennas on the vertical walls of the helical array. These operate at 2.45 GHz and use the pilot beam received from the ground station to provide a reference for the microwave beam. The peak intensity of the microwave beam at the centre of the rectenna on the ground is 245 W/m^2. Each system generates 1.44 GW of electrical power into the grid.

The design of a SBSP system is a balance between a number of competing factors; minimising the size of the satellite whilst limiting the thermal load on the PV to optimise their efficiency and limiting the maximum microwave intensity at the ground. For the purpose of this investigation the typical mass breakdown of the key elements of the satellite is detailed in Table 3-1

Table 3-1 Typical Satellite Mass Breakdown for 1.44 GW system

Satellite Sub System	Mass (kg)
PV	1,349,200
Reflector	158,600

Wireless Power Transmission	358,400
Thrusters	2,100
Communications and Control	9,500
Structure	186,400
Total	**2,064,200**

3.2.2.2 Ground Station

Functionally the ground station can be considered as two separate systems; one that receives the microwaves, generated electricity and connects to the grid, the other that controls the satellite and manages the communications. There are many commercial models that could be employed for an operational system. A likely approach is for different organisations to operate the satellites and the power stations. A satellite operator might have a number of satellites, which they control from a single operations centre. They would sell microwave power to the power station operators, who in turn sell the electricity they generate into the grid. The key element of the Power Station is the rectifying antenna or rectenna. The rectenna receives the microwave beam and generates DC electricity. It will be sized to capture the majority of energy in the beam.

The structure of the rectenna is relatively simple; a grid of interconnected rectifying antennas placed about 100mm apart supported on a suitable structure. The rectenna could be placed on land or offshore. The rectenna grid is relatively open, so there is the possibility that the area of land covered by the rectenna could also be used for other purposes, recognising the local effects of the microwave field.

The power control system within the power station operates in a very similar way to terrestrial solar farms. It will use very similar systems to condition the DC electricity generated by the rectenna, convert to AC electricity and manage the power flow to the grid. The power station will also generate the retrodirective pilot beam that provides the solar power satellite with the target point for the microwave beam.

3.2.2.3 Enabling Systems

The enabling systems cover the elements necessary to bring the core power system into operation. They are divided into those that support the in-orbit systems and those that support the ground systems, with spacelift providing the bridge between the two.

The construction of the satellites will rely on autonomous in-orbit assembly. The satellites will be made from connecting a large number of modules together. There will be relatively few different types of modules. The modules will be designed for robot assembly. It is envisaged that the robots will be a similar size to the modules and will travel over the satellite structure as they build it, replicating the way that ants and termites build their structures [11]. The robots will remain on the assembled structure and will be available for subsequent maintenance of the satellite, removing and replacing failed modules.

The size of the satellite dictates that it will require a sequence of launches to transport all the material to the final orbit. The satellite structure and modules will be designed for efficient packing in the payload bay of the chosen launch system and then subsequent autonomous in-orbit deployment and assembly. A number of strategies to deliver the systems to the final orbit have been proposed. It is envisaged that a reusable launch vehicle will deliver its payload to a suitable transfer orbit and then an orbit transfer vehicle will raise the payload to its final orbit.

Decommissioning strategies for satellites are still in their infancy. The current trend for satellites in the higher orbits, such as geostationary orbits, is to lift them into a graveyard orbit at the end of their life. This is the current working assumption for solar power satellites. Nonetheless, by 2040 when these systems start to be operational it is reasonable to expect that better strategies will be available; strategies that significantly extend the life of the system by continuous replacement of failed modules and measures to reclaim and reuse the material from failed modules.

3.2.2.4 Energy Chain

To assess the system costs a range of efficiencies are defined, which enable the power at each stage of the system to be calculated. Efficiency ranges are based on published information where possible, or subject matter expert option otherwise. They include the full power flow, from in-orbit solar power collection, through high-concentration photo voltaic (HCPV) conversion efficiency, to transmission (DC to RF efficiency), and finally on-ground RF power received, distributed and collected, culminating in 1.44 GW power into the grid. A detailed breakdown of the power flow estimate ranges and power outputs can be found in TN3 [3].

3.2.2.5 Power Network Integration

One of the attractive features of a grid connected SBSP generation system is that it provides predictable and continuous power which is dispatchable — i.e., the power output can be matched to demand. Apart from brief periods when the satellites are in eclipse or the power beam has to be interrupted to avoid interference and during scheduled maintenance, the power station will provide power continuously. The satellite will go into eclipse for short periods of time each day for around 45 days around each equinox. The duration of each eclipse starts at a few minutes and steadily increases to maximum of about 70 minutes at the equinox and then steadily reduces to a few minutes.

Two strategies are considered to estimate the power station load factor (total power delivered as a proportion its rated power), one which assumes a one hour per day stop in generation to cover periods of eclipse (or other interruptions), and another which assumes half an hour per day where the system is offline to allow time to re-establish the power beam, resulting in load factors between 95% and 98.5% respectively. The characteristics of SBSP, in particular the combination of firm and dispatchable power, reduces the burden on the grid to provide such system flexibility.

3.2.3 Technical Maturity Assessment

The technical feasibility assessment uses the system breakdown introduced in section 3.2.2 as the basis for an evaluation of the technology maturity and development degree of difficulty to highlight the challenges of introducing an operational system by 2040, at the latest.

Technology Readiness Levels (TRLs) provide a scale to measure the current maturity of the technologies required to realise a system. The TRL scale we have used is based on ISO 16290 and described in Annex A.6. The development degree of difficulty (DDD) is used to establish and assesses the difficulty in taking the technology from its current maturity to an operational system. The DDD scale is based on a similar scale used by NASA [13] and described in Annex A.7. Together they can be used to assess the feasibility of the technology. The full technical feasibility assessment is presented in Annex A3 with further discussion in Annex A4 of TN3 [3]. A summary overview is presented in Table 3-2. The combination of TRL and DDD can be used to highlight the development priorities for the system, concentrating first on the elements with lower TRL and higher DDD.

Table 3-2 Technical Feasibility Summary

Subsystem element	TRL	Development Degree of Difficulty
Core Power Systems		
Satellite		
Satellite collect	5	High
Satellite convert	2	Medium
Satellite transmit	4	Very High
Satellite structure	3	Very High
Satellite thermal management	3	High
Satellite control system	4	Medium
Satellite station keeping	3	High
Satellite communications	6	Low
Ground Station		
Ground receive	4	High
Ground convert	7	Low
Ground distribute	7	Low
Ground grid connection	8	Very Low
Ground structure	7	Low
Ground control system	6	Medium

Subsystem element	TRL	Development Degree of Difficulty
Ground operations: Power Control Interface	8	Low
Satellite operation: Mission Control Interface	4	High
Ground communications	4	Medium
Enabling Systems		
Satellite		
Spacelift	7	High
Satellite manufacture (ground)	6	Low
In-orbit assembly	3	Very High
In-orbit maintenance	3	Very High
Decommission satellite	2	Very High
Ground Stations		
Rectenna manufacture	4	Medium
Power station construction	8	Very Low
Operation station construction	8	Very Low
Maintenance of ground stations	7	Very Low
Decommission ground stations	8	Very Low

3.2.4 Technical Challenges

The combination of TRL and development degree of difficulty discussed in section 3.2.3 can be used to identify potential high priority areas for development. On the basis that those elements with the lowest maturity and highest difficulty are likely to take the longest to develop, it would make sense to prioritise effort in those areas.

Another way to look at the challenges is to consider which areas of development are specific to SBSP. Some elements of the system will be able to draw upon parallel technical developments that are being made for other applications, others will need to be driven by a SBSP development programme. Taking these two approaches into consideration reveals that development of the following systems should be prioritised:

- **Wireless power transmission (WPT)** - Whilst the physics of WPT are well understood, the longest distance over which meaningful power has been transmitted is of the order of a kilometre [14]. This is a very small compared with the required beaming distance from geostationary orbits (i.e. over 35,000 km). While it is possible to demonstrate some increase in the beaming distances by using a high-altitude platform station (HAPS) to demonstrate WPT from the upper atmosphere, ultimately it will be necessary to put a demonstration system into orbit to demonstrate WPT over meaningful distances for SBSP.
- **Solar collection optimisation** - The overall size of the satellite is determined by the efficiency of the energy chain. Increasing the efficiency reduces the size (and therefore cost) of the satellite for a given power delivery. The solar collection and conversion elements, essentially the photovoltaic system, has the lowest efficiency in the energy chain. Therefore, improving solar collection and conversion efficiency will have the biggest effect on improving the overall efficiency.
- **In-orbit assembly and maintenance** - The required size of the satellite dictates that it will need to be delivered in a number of packages that are deployed and assembled in-situ. The location of the orbits suggest that the assembly will have to be carried out by autonomous robots. Whilst there are significant developments currently being made in in-orbit service and manufacture (IOSM), these are predominately focussed on a different market. The IOSM vehicles are of a comparable size to the satellites they are servicing and are able to interface to a number of different types of satellite. The in-orbit assembly robots for a solar power satellite are likely to be bespoke elements of the satellite system, drawing their power from the satellite and using the satellite as a support

structure. The design of the robots will need to evolve in tandem with the design of the satellite modules they are handling.

- **Structural design of satellite** - The satellites will be orders of magnitude larger than any currently orbiting structure. Therefore, there is a lack of understanding of the necessary structural design requirements. There will be a need to minimise the mass of the satellite whilst providing sufficient rigidity to maintain the functional performance of the key systems.

- **Decommissioning strategy -** The satellite needs to be designed from the outset for a robust and responsible end of life strategy. This includes exploring measures to maximise the service life of the satellite components, taking into account the environmental effects encountered in the chosen operational orbit, resilience to damage and ongoing maintenance and upgrade. The design concept for CASSIOPeiA has not yet developed an end of life nor space debris mitigation strategy. In the absence of a more developed strategy the cost model assumes that the satellite will be moved to a graveyard orbit at the end of its life.

- **Spacelift strategy -** SBSP will rely on a vibrant commercial spacelift service. Conversely, SBSP provides a potential market for commercial spacelift providers. There are two elements of the spacelift strategy to be considered, delivery to a transfer orbit followed by orbit raising with an orbit transfer vehicle. There are various space-lift options, some of which impact on the design, for example considering the size and shape of the launch payload bay. Approaches to orbit transfer will also impact on design consideration and so close collaboration between SBSP developers and launch service providers would be required. For this study, the assumption that satellite modules will be delivered to the final orbit by a transfer vehicle powered by chemical rocket.

- **Non-technical challenges** – in addition to the technical challenges described above, there will be many non-technical challenges that should be considered during development, because the are likely to impact on the solution design. They include:

  - **The safety of the system and equipment** – for example the effects on other spacecraft (in lower orbits) of passing through the RF power beam and the tolerance of the satellite to debris, including the prevention of debris shedding.

  - **Safety of people and wildlife** - agreements on acceptable safe RF beam intensity, both above and outside the rectenna, and strategies to ensure safety if beam lock lost and beam wanders off the rectenna will be required.

  - **Environmental** – the effects of microwaves on flora, fauna, and the atmosphere, as well as carbon intensity will need to be better understood.

  - **Standards** – a new energy generation technology will require new standards, especially the formation of international standards to allow interoperability between sub-system elements.

  - **Security** – to maintain control of the satellite and the beam, ensuring security of a critical national infrastructure.

  - **Public acceptability -** There will need to be a properly coordinated information programme to that the public receive the appropriate information so they can make informed decisions rather than be influenced by conspiracy theories.

3.3 Cost Estimates

The CASSIOPeiA reference design used in this study is in its early stages of concept design and aspects of the underpinning technology are in early stages of development. Therefore, the system it is too early in the development cycle for the specification and final design of a particular installations to have been defined. As a result, there is considerable uncertainty in the expected performance and therefore cost of a future system. To reflect this uncertainty a probabilistic parametric cost model has been used to derive cost estimates. Consequently the model produces probabilistic distributions of the output costs. For convenience the 10%, 50% and 90% costs are highlighted in the results (denoted p10, p50 and p90 respectively). The model used was first created by Frazer-Nash as part of the space-based solar power study for BEIS, UK government [18].

The cost model estimates the size of the system elements based on physical relationships, such as power conversion efficiencies or diffraction physics. The parameter which defines the scale of the system is given in the input data. For example, the scale of the satellite reflector is parameterised by area and is calculated based on solar power density and the required power. The cost of the system elements is based on a relevant cost estimating relationship, such as cost per unit area or cost per unit mass. The model is able to apply learning factors to account for the cost reductions that are experienced in volume manufacture

3.3.1 Opex and Capex – First of a Kind System in Europe

The model calculates operational expenditure (Opex) and capital expenditure (Capex), and derives a levelised cost of electricity (LCOE) value using an industry standard formula (see TN3 [3]). The cost elements are shown in Table 3-3.

Table 3-3 Cost Model Opex and Capex Elements

Cost Area	Cost Element
Opex	Connection
	Operation
	Insurance
Capex	Satellite
	Rectenna
	Land
	Control
	Balance of Plant
	Launch Insurance
	Spacelift
	Assembly
	Ground Station Construction Pre-development
	Infrastructure
	Engineering Team

The primary results of this study estimate a first of a kind (FOAK) SBSP system in current year (2022) prices (€), using a European-wide average for the satellite elevation angle and land prices, and a 20% hurdle rate.

Figure 3-5 shows operational and capital expenditure for a 1.44 GW FOAK SBSP system. Opex over the 30-year operational life is estimated to be between €2.5bn (p10) and €3.5bn (p90). Capex is estimated to be between €4.8bn (p10) and €9.8bn (p90). The total costs (excluding development) of a first European SBSP system has an estimated range between €7.3bn (p10) and €13.3bn (p90).

Figure 3-5 Operating and Capital Expenditure for the Averaged Five European Countries with a 1.44 GW FOAK SBSP System in Cash Terms

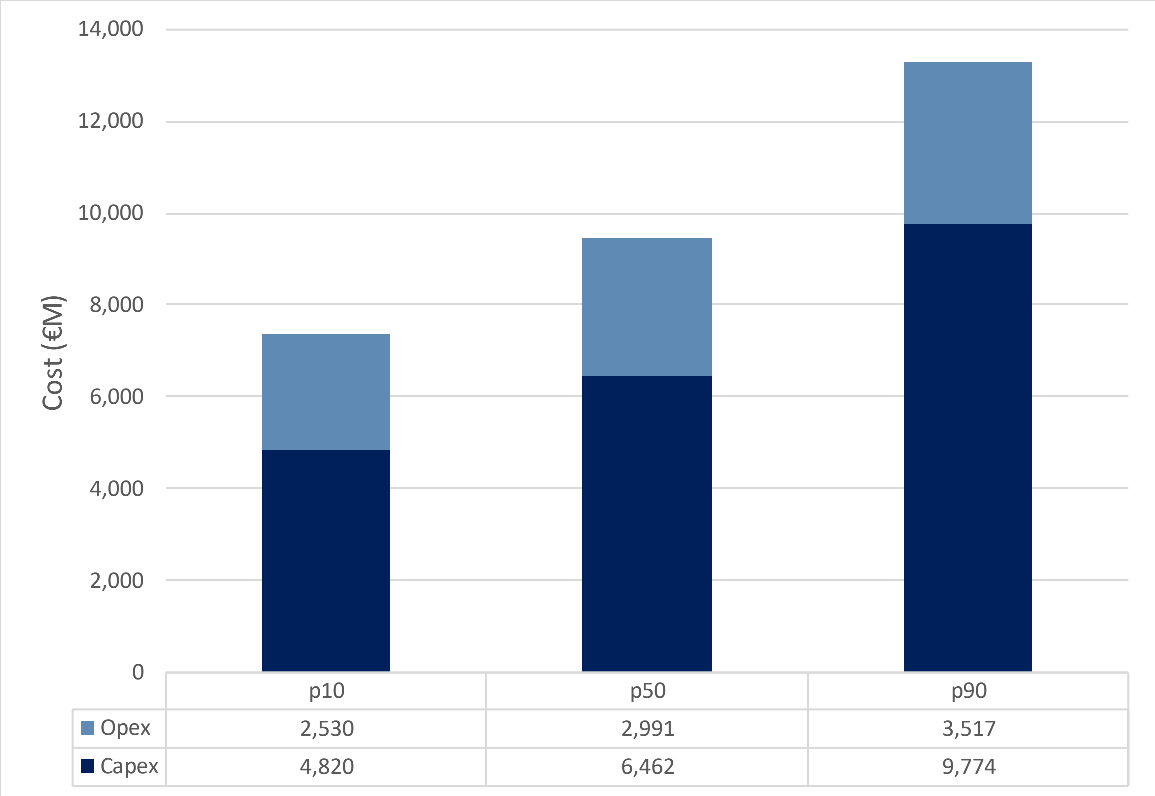


Table 3-4 Breakdown of Opex and Capex breaks down the total expenditure into its constituent parts. Spacelift cost, which is part of the enabling systems costs is the most expensive element associated with the implementation of the system, with a cost range estimated to be between €1.24bn (p10) and €6.08bn (p90). Cost estimates were made for the top 5 largest energy consumers in Europe, to illustrate how the characteristics of each country affect the system costs. The assessment considered differences in land value, country specific inflation rates and the required land footprint, based on (average) latitudinal locations. The results show a fairly narrow range of Capex between €9.5bn (France (p90)), and €9.9bn (Germany (p90)), and Opex between €3.3bn and €3.6bn respectably (p90).

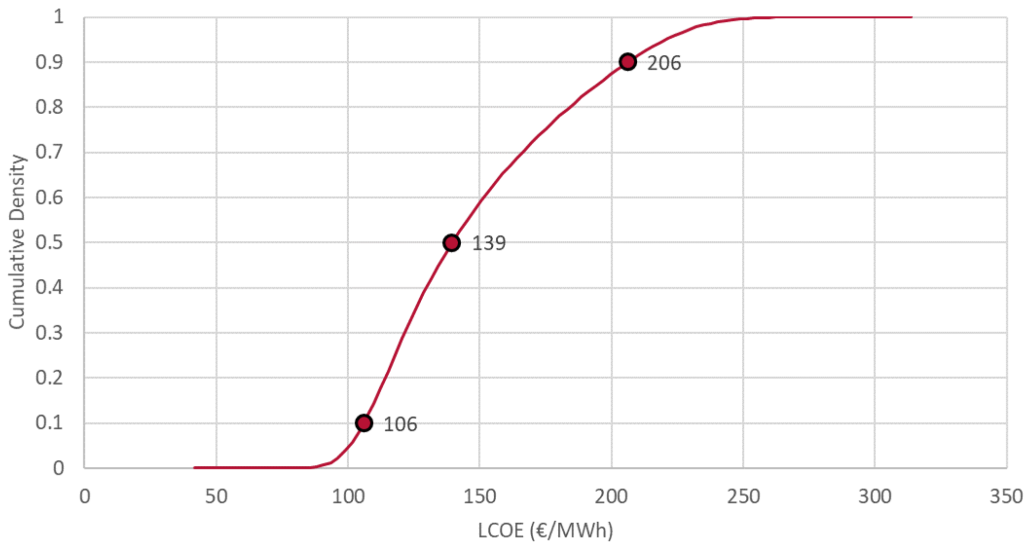
Table 3-4 Breakdown of Opex and Capex

CAPEX		OPEX	
Ground Stations	17.6%	Connection & Use	1.9%
Satellite	37.2%	Operations	40.6%
Enabling Systems	45.3%	Insurance	57.4%

3.3.2 Levelised Cost of Electricity (LCOE)

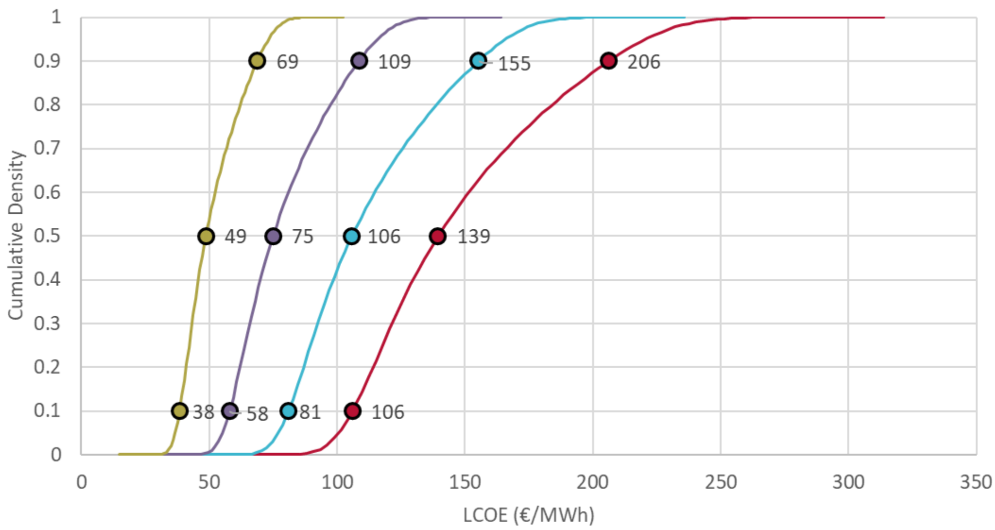
A European-wide average LCOE was computed for a 1.44 GW FOAK system using average elevation and land cost data, and a 20% hurdle rate. Figure 3-6 plots the cumulative distribution function for the LCOE which shows an expected range between €106/MWh (p10) and €206/MWh (p90).

Figure 3-6 Predicted LCOE for the Averaged Five European Countries with a 1.44 GW FOAK SBSP System



The results above have been presented with a 20% hurdle rate, however, once the development programme has been completed the perceived risk profile of the project may reduce. This will have an impact on the financial return that the investors who finance the construction and operation of the system will expect. Therefore, the LCOE has been calculated for a range of hurdle rates to represent possible variation in the cost of capital to the SBSP organisation (Figure 3-7).

Figure 3-7 LCOE Sensitivity to Chosen Hurdle Rate (5% - mustard, 10% - purple, 15% - blue and 20% - red) for the averaged European SBSP FOAK System

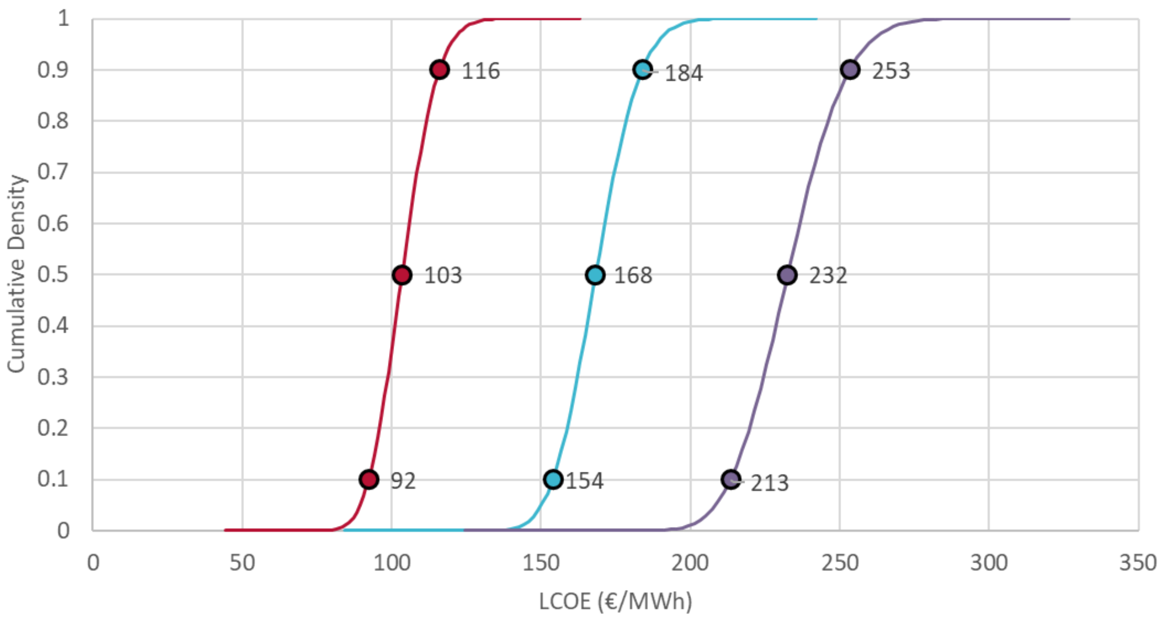


As indicated in Table 3-4, Spacelift cost is the largest cost element of Capex and hence LCOE. Whilst the cost analyses presented above use a distribution of spacelift costs, a sensitivity analysis explored the variation of LCOE if the spacelift costs are fixed. To provide a comparison the analysis examines the LCOE with spacelift cost (euro) per kg to GEO fixed at the lowest, median, and highest value from the dataset[5]. They are:

- 454 €/kg
- 1,877 €/kg
- 3,301 €/kg

The results of the sensitivity tests (Figure 3-8) demonstrate that spacelift costs significantly affect the LCOE, and that fixing the spacelift cost reduces the variance in LCOE across the probability range from 10% to 90%. If the spacelift cost can reflect costs observed with reusable rockets in the USA that are launched via the public/private partnership between NASA and SpaceX (~€400/kg), then the LCOE of SBSP is highly competitive compared to other electricity generating assets.

Figure 3-8 LCOE Sensitivity to Space Lift Costs Varying from Low (red - 454 €/kg), Median (blue – 1,877 €/kg) and High levels of Space Lift Costs (purple – 3,301 €/kg)



Further sensitivity analysis was carried out on the mean of the structural mass ratio, which concluded that the LCOE is relatively insensitive to changes in the structural mass ratio. While mass of the overall system is a key factor that influences the overall system cost, the change in overall mass that needs to be put into orbit is relatively small.

3.3.3 Development Costs

Development costs for the four phases presented in the detailed roadmap (section 3.5) were estimated by adopting a hybrid approach of benchmarking and detailed bottom-up costing, as described in Annex A.2. The results are shown in Table 3-5.

[5] See TN4, Annex A4.

Table 3-5 Development Cost Estimates

	Phase 1 Ground based WPT trials.	Phase 2 40 MW scale demonstrator in polar orbit	Phase 3 500 MW demonstrator in an operational orbit	Phase 4 Full scale production prototype in an operational orbit
Duration	5 years	5 years	4 years	4 years
P10	€115M	€495M	€2,275M	€4,755M
P50	€140M	€600M	€2,680M	€6,755M
P90	€170M	€725M	€3,610M	€11,260M

The phase durations presented in Table 3-5 are illustrative, based on a reasonable spend profile. The cost estimates do not depend on the elapsed time of the phase. In principle the phases could be completed in less time depending on the appetite for risk and if the resources could be mobilised and properly controlled. For phases 2, 3 & 4 it is assumed that the operational trials of the satellite will take place over the last 2 years of the phase.

Benchmarking these development costs is a challenge. While a significant proportion of the costs are associated with space elements, the characteristics of the satellite and its supporting systems are more akin to consumer electronics than traditional space systems. Traditional space systems tend to be developed, manufactured and put into service as single units. SBSP represent a different class of system, where hyper-modularisation means that the costs will reduce as manufacturing volumes increase. In this respect they are more akin to consumer electronics or automotive manufacture than traditional satellites. As a comparison, there are some commentators that say it cost SpaceX 10 billion dollars over 10 years to design, build and deploy the 2,300 mass-produced Starlink satellite constellation.

3.4 Cost-Benefit Analysis

3.4.1 Study aims

TN4 [4] presents an assessment of the benefits, costs, and risks associated with a potential European SBSP capability for terrestrial energy needs, including impact of SBSP on Europe's energy supply and climate change efforts. This analysis aims to provide the European Space Agency and its Member States with information regarding the potential of SBSP to meet Europe's strategic energy needs, including contribution to the goal of achieving Net Zero carbon emissions by 2050, and to inform early actions that might be required to make this capability a reality.

Further analysis of the benefits of SBSP for individual countries – France, Germany, Italy, Poland, and the UK – is presented in a separate report (TN4.1 [7]).

3.4.2 Study scope

Benefits are assessed holistically for strategic, economic, environmental, and societal characteristics and quantified where possible. These benefits are then compared against the development, capital, and operating costs for implementing the system relative to a counterfactual where there is no SBSP capability in Europe.

The time period of analysis is from 2022 to 2070, with appropriate discounting to account for the long timeframe and large uncertainty and technical risks of the project. Sufficient time for the research and development phase would allow for the launch of the first fully operational prototype satellite by 2040, with an assumed system lifetime of 30 years given its modularity. The system is then assumed to scale-up to meet an estimated 'demand for SBSP' figure. The SBSP system is assumed to cover the European landmass, and costs and benefits focus on the 30 countries that are ESA Member States or EU Member States (or both).

3.4.3 Net Zero context

In order to understand the impact of SBSP, it is important to characterise the energy market as it will be in the absence of SBSP. This requires an understanding of how the demand for energy and the supply of energy generation technologies that will meet this demand is expected to evolve over the time period of analysis. A summary of this context is presented below.

Many European countries and the European Commission have set out ambitions to limit their greenhouse gas emissions, and ultimately to reach climate neutrality, i.e. Net Zero emissions, by 2050. The International Energy Agency (IEA) considers Net Zero by 2050 to be a "**narrow but achievable**" aim.

Emissions from fossil fuels such as oil, gas or coal for energy production are among the largest sources of greenhouse gases in Europe. It is expected that key tools used to meet climate goals will include **replacing fossil fuel energy generation with renewable energies**; increasing the **electrification** of the economy; increasing **energy efficiency**; and **offsetting remaining emissions** from "hard to abate" sectors.

This analysis considers two potential future scenarios (both in the absence of SBSP) – the "Net Zero scenario" in which Net Zero targets are reached; and a separate "business as usual" (BAU) scenario in which Net Zero targets are missed.

Under the **Net Zero scenario** which forms the reference scenario for the cost-benefit analysis (Table 3-6), electricity demand across Europe is expected to stand at around 250% of current levels by 2050, increasing to almost 8,000 TWh annually. This large-scale expansion of electricity generation reflets increasing electrification of the economy, and a greater role for clean energy sources. As a result, the electricity supply will be almost completely decarbonised, with renewable energy sources meeting over 80% of electricity demand by 2050; a continuing role for nuclear power (around 10%); and a much smaller role for natural gas and coal.

Table 3-6 NZ2050 Europe Total electricity generation by source fuel (GWh)

Source fuel	2020	2025	2030	2035	2040	2045	2050
Solid fossil fuels	390,009	272,212	198,580	160,679	124,065	78,280	29,165
Crude oil and petroleum products	29,227	12,587	9,861	12,714	15,566	18,418	21,271
Natural gas	617,147	539,406	452,309	383,766	326,196	260,644	192,344
Nuclear	741,170	623,100	576,346	633,257	641,602	678,353	746,466
RES	1,364,249	1,930,827	2,562,052	3,696,117	4,757,475	5,806,023	6,856,185
Other	2,378	4,132	10,966	26,220	34,415	38,038	41,955
TOTAL	3,144,180	3,382,263	3,810,114	4,912,753	5,899,318	6,879,755	7,887,387

Note: Figures may not sum precisely due to rounding

Source: LE analysis

Under the alternative **BAU scenario**, electricity demand across Europe increases by around one third by 2050 compared to current levels, increasing to just over 4,000 TWh annually given lower levels of electrification. Renewable energy sources meet the majority of electricity demand by 2050, with nuclear supplying over 10% of electricity. Natural gas continues to play a substantial role in electricity production in this scenario.

Both scenarios suggest a major change in the way energy is consumed across Europe, with electricity making up a greater portion of overall energy demand. The electricity that is generated will be much **less CO2 intensive** in large part because of the deployment of far greater capacity of renewable technologies.

The prominent role of intermittent renewable electricity sources such as wind and solar implies additional needs to ensure stability of supply. These electricity sources are weather dependent and the output is therefore variable both across time of day and over the year. The baseload expected to be provided by nuclear is likely not sufficient, especially in the Net Zero scenario, so alternatives are required.

Country level differences exist in electricity generation between the five largest-emitting countries in Europe, with France's electricity mix much more reliant on nuclear (and therefore less carbon intensive). Germany is planning to close its nuclear plants and may become more reliant on coal in the short-run. Poland's coal use is the largest in the EU and remains the largest component in that country's energy mix. The UK plans to decarbonise its electricity supply by the mid-2030s, while Italy is expected to dedicate a large share of electricity to the production of hydrogen, particularly in overgeneration periods.

These scenarios involve substantial uncertainty as they project electricity demand and supply to 2050 and beyond. They are not intended as predictions but as "reasonable" counterfactual scenarios that could occur in the absence of SBSP.

3.4.4 Competitiveness of SBSP

The role of SBSP in the future European energy mix will in large part depend on its cost competitiveness relative to alternative sources of electricity generation.

One measure of the cost-competitiveness of an energy-generating technology is the Levelised Cost of Electricity (LCOE). The LCOE estimates the average price at which the electricity generated must be sold to break even on the investment. LCOE enables comparisons between different technologies with different lifetimes, generation capacities, and investment risks.

LCOE has some drawbacks: it does not incorporate the 'social cost of carbon' and other negative externalities; fails to capture specific technological and regional aspects of a given project and does not measure the indirect costs to the energy system as a whole.

VALCOE, the 'value adjusted' accompaniment to LCOE, aims to address some of LCOE's shortcomings. It achieves this by including three new terms in the calculation: the energy value, flexibility value, and capacity value adjustments. A negative adjustment suggests improved cost-competitiveness. The energy, flexibility, and capacity adjustments respectively capture the price received for energy sold over the market average (indicating ability to react to the market); the value of additional flexibility brought to the network, and the value created by contributing to the minimum capacity requirement of a network.

Table 3-7 LCOE and VALCOE 2040, by energy source (2022 prices, €/MWh)

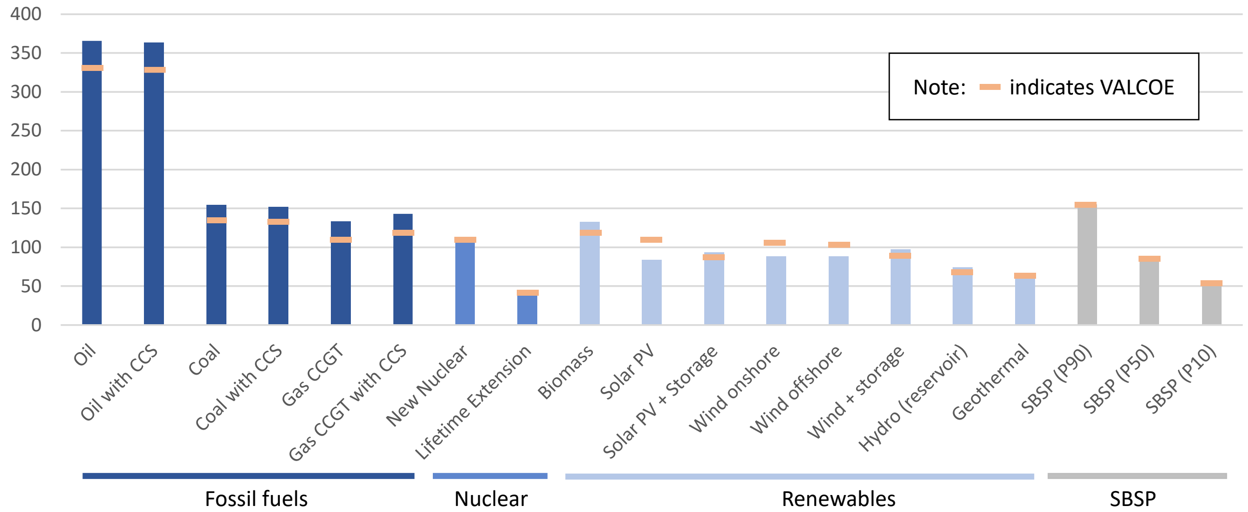
Macro group	Subgroup	Generation technology	LCOE	VALCOE
Fossil fuels	Oil [B]	Oil	365.7	339.0
		Oil with CCS	363.2	336.5
	Coal [I]	Coal	154.7	128.1
		Coal with CCS	152.2	125.6
	Gas [I]	Gas CCGT	133.2	105.5
		Gas CCGT with CCS	143.2	115.5
Nuclear [I]		New Nuclear	107.9	107.9
		Lifetime Extension	43.1	43.1
Renewable		Biomass [F]	132.5	104.7
	Solar [I]	Solar PV	83.9	101.9
		Solar PV + Storage	93.2	87.8
	Wind [I]	Wind onshore	88.3	102.5
		Wind offshore	88.3	102.5
		Wind + storage	97.6	88.3
		Hydro (reservoir) [T]	74.7	61.1
		Geothermal [T]	67.1	67.1
SBSP	NOAK	10th of a kind, 90th percentile	155.5	155.5
	NOAK	10th of a kind, 50th percentile	88.5	88.5

***Sources:* [I]: International Energy Agency (2020), *European Union 2020 Energy Policy Review*;**
[F]: Fraunhofer ISE (2021), *Levelised Cost of Electricity of Renewable Energy Technologies*;
[T]: Trinomics (2020), *Final Report Cost of Energy (LCOE), EC DG Energy*
[B]: BEIS. (2020). *Electricity Generation Costs 2020*
Notes: 'CCS' = 'carbon capture and storage', 'SBSP' = Space Based Solar Power'. The value adjustments to SBSP are considered to be broadly similar to Nuclear, and therefore the total value adjustment assumed for SBSP is 0 – meaning the VALCOE equals the LCOE.

An extensive literature review suggests that aggregate value adjustments are negative for fossil fuels, intermittent renewables with storage, and hydro (they became relatively more cost-competitive); negligible for nuclear power (the adjustments cancel each other out), and positive for other intermittent renewables without storage (i.e. they become relatively less cost competitive on a value-adjusted basis). Space Based Solar Power is determined to be most similar to nuclear in terms of value adjustment parameters, and so no value adjustment is made to SBSP's LCOE as is the case for nuclear. Indicative analysis by London Economics using secondary data sources produced the following estimates for LCOE and VALCOE for each energy producing source:

The data presented in Table 3-7 is presented graphically in Figure 3-9.

Figure 3-9 LCOE and VALCOE, by energy source (2022 prices, €/MWh)



Sources: London Economics based on data from **[I]: International Energy Agency (2020), *European Union 2020 Energy Policy Review*;**
[F]: Fraunhofer ISE (2021), *Levelised Cost of Electricity of Renewable Energy Technologies*;
[T]: Trinomics (2020), *Final Report Cost of Energy (LCOE), EC DG Energy*
[B]: BEIS. (2020). *Electricity Generation Costs 2020*

This analysis suggests that SBSP is more cost-competitive than oil, and approximately equivalent to coal, gas, and biomass, and less competitive versus the remaining power generation technologies on LCOE and VALCOE terms. SBSP experiences a relative improvement in competitiveness against solar PV *without* storage and most types of wind when moving from LCOE to VALCOE comparisons. On the other hand, SBSP becomes relatively less competitive versus fossil fuels when moving from comparisons on a VALCOE rather than LCOE basis.

When further adjustments are considered (including taxes and subsidies) it is believed that SBSP could become even more price-competitive with other production options in the energy mix – particularly fossil fuels which may be subject to increasing carbon taxation in the future – implying a financially rational motivation for investment in SBSP.

A risk-adjusted discount rate or 'hurdle rate' of 20% is used when evaluating the LCOE of SBSP. This is based on reports on similar types of projects and theory. Sensitivity analysis indicates that lowering the discount rate would make SBSP more competitive in VALCOE terms by up to 50% when using a 10% discount rate.

Taxes or subsidies for SBSP could be used to account for externalities of different energy sources that are not captured in the LCOE. The choice of economically optimal levels of taxes and/or subsidies for SBSP are impossible to determine with any certainty since externalities are untraded and therefore lacking accurate pricing information. Suboptimal levels of taxes and subsidies are distortionary and will likely imply a large fiscal burden on electricity buyers (in the case of taxes) or government (in the case of subsidies).

3.4.5 Scale of SBSP

3.4.5.1 Demand for SBSP

In a market economy, price is the key determinant of the employment of goods and resources. In the absence of government intervention, price as captured by the VALCOE, would therefore be the determinant of the make-up of the supply mix of the electricity market across Europe. However, the potential of energy sources can also be assessed against other non-price attributes, including their contribution towards achieving Europe's climate neutrality targets, and ensuring security of supply to the electricity grid.

Key determinants of the demand for SBSP therefore include the (Value Adjusted) Levelised Cost of Electricity, the nature of the energy source in terms of its dispatchability, and the social cost of carbon that characterise each energy production technology.

For example, on a pure cost basis, SBSP outperforms oil, and is approximately equivalent to coal, biomass, and gas on an LCOE basis (albeit weaker on a VALCOE basis). SBSP, however, is a firm and dispatchable source of electricity that helps improve grid stability and ensures supply in all weather. Compared with wind and solar, there is therefore a different argument for the use of SBSP. Likewise, VALCOE or LCOE estimate fails to account for the social cost of carbon. This cost exceeds the carbon pricing used in VALCOE and LCOE estimates and suggests that fossil fuel energy sources impose much larger costs on society than is implied by comparisons of VALCOE and LCOE. Finally, nuclear power, whilst not emitting CO2 and providing stability and dispatchability, is not a solution to all problems. There are political sensitivities in many European countries that make nuclear a difficult proposition, nuclear waste is not straightforward to handle and needs careful treatment to ensure it is not harmful for humans – for millennia, and, last but not least, nuclear fuel is not available in nearly the required quantities within Europe, resulting in energy reliance on a small number of foreign states, including Russia. For this reason, it is asserted that the new nuclear installations foreseen in the Net Zero scenario could be displaced by SBSP.

The results from the analysis of demand for SBSP are found in the table below. The table shows the amount of electricity that is displaced by SBSP for each generation type, relative to the Net Zero scenario.

Table 3-8 Total counterfactual supply (GWh) from energy sources potentially displaced by SBSP (90th percentile)

Net Zero scenario	2040	2045	2050
Wind + Storage	0	104,484	209,150
Solar PV + Storage	0	37,974	75,916
Solid fossil fuels (total including with and without CCS)	124,065	78,280	29,165
Petroleum products (total including with and without CCS)	15,566	18,418	21,271
Natural and manufactured gases (total including with and without CCS)	326,196	260,644	192,344
New nuclear	0	55,166	80,774
Total "maximum possible" demand	**465,827**	**554,966**	**608,619**

Note: the total demand is defined as the Net Zero scenario counterfactual demand for fossil fuel energy sources, plus 15% of any **additional** renewable and nuclear sources that are expected to begin supplying electricity after 2040.

Source: LE analysis of European Commission scenarios to deliver the European Green Deal, BEIS Projection of electricity generation by source, and other national data sources

Given an average annual yield of around 11.3 TWh[6] of gross electricity generation to the grid from a single 1.44 GW SBSP satellite, the above analysis suggests that European demand for SBSP is in the order of **41 satellites** in 2040, **49 satellites** by 2045 and **54 satellites** by 2050. These numbers represent the potential number of satellites required to meet demand if SBSP were introduced in the years highlighted.

However, it is unrealistic to consider that SBSP could supply in excess of 465 TWh of electricity by 2040. In reality, there will be supply constraints that limit the SBSP programme from reaching this very large theoretical "maximum", unless there was a politically mandated, "war effort"-like industrial mobilisation for clean energy sources including SBSP.

3.4.5.2 Supply constraints for SBSP

Supply constraints that may limit the achievement of the theoretical maximum demand described above run through four broad categories:

1. Availability of land to site the rectenna
2. Industry's ability to meet demand for space and ground infrastructure
3. Launch capacity
4. Political, regulatory, and legal constraints

Considering each of these issues in turn, the size and requirements of rectennas mean that there are limits to where they can be sited within the comparatively dense regions of Western and Central Europe. The footprint of rectennas depend on the geographic latitude of their placement, but each will occupy approximately 50 km^2 of contiguous land on average and must meet the criteria :

- Not located in a national park
- Not located on a railway
- Not Located on a "Major Road"
- Not located on a waterway
- Not located in an urban area
- The area fits the size of rectenna

While the size of the investment in SBSP would justify enabling actions such as rerouting roads or railways, the number of available sites in individual countries is limited. This study investigated the feasibility of siting rectennas in five European countries (France, Germany, Italy, Poland, and the UK) and found approximately 6,500 available sites. This implies that the geographic space is available, but effort is required to procure the land, ensure planning permission is granted, and obtain public buy-in given their potential visual impact on the landscape. The ability of rectenna sites to support dual-use of the land in which they sit on (e.g. with agriculture) may mean that rectennas could be collocated in a larger number of sites than implied by the geospatial analysis conducted for this study.

Although this analysis suggests that the identification of appropriate sites for the location of rectennas is unlikely to pose a constraint on the SBSP programme (given the level of possible demand for electricity that can be serviced by SBSP), the ability of industry to meet the demand for satellites could pose a constraint.

The System Build Rate – or the ability of European industry to meet demand for space and ground infrastructure – is determined by:

[6] Average annual yield data sourced from the Frazer-Nash cost model, assuming 90th percentile of the cost model

- Technological development
  - Enabling technologies are required to deliver the SBSP concept, including Wireless Power Transmission (WTP), high-efficiency semiconductor technology, Heliostat Concentrator Photovoltaic (HCPV) technology, mass manufacture of space-grade electronics, highly modular construction, and autonomous robotic assembly in space. These technologies are at early technology readiness levels and therefore requirement significant investment and lead times to mature.
- Industrial capacity
  - Industrial capacity is driven by the factors of production: **land**, **labour**, and **capital**. As discussed above, there is sufficient **land** available to site rectennas and factories if required. The supply of the skilled **labour** required to construct the infrastructure is affected by competing demands from other high-value manufacturing sectors and the overall supply of engineers is notoriously reported as insufficient. A dedicated activity to ensure supply of labour is recommended. Access to **capital** depends on the financial viability of the SBSP programme. Government also has a role to play to ensure capital is deployed in the most efficient manner and not suffering any market failures.
- Political, regulatory, and legal constraints
  - Public acceptance is a key challenge for the SBSP programme and efforts to demonstrate the low risk of the specification must commence as soon as the programme starts. Additional issues could include orbital slot and frequency allocation.

The supply of launch services to deliver SBSP into geostationary transfer orbit (GTO) will also be a major constraint to Cost-Benefit Analysis (CBA) model assumptions, as elaborated in Annex A.9. This issue can be understood by considering the total launch requirement of a single 1.44 GW SBSP system under a conservative assumption of availability of heavy-lift launch service:

- The total spacelift mass that is needed to put a 1.44 GW SBSP system into orbit is 2,491 metric tons. This is equal to the satellite mass of 1,816 metric tons plus the mass of station keeping propellant, assembly robots, and OTV[7].
- Starship, a planned fully reusable super heavy-lift launch vehicle that is being developed by SpaceX, represents the only near-term launch concept which can deliver SBSP's modular structures to GTO at a reasonable cost and in the right orbit. This system can deliver a total mass of between 21-29 T to GTO[8], assuming that Starship is refuelled in orbit using propellent that is also delivered to GTO.

Taken together, these two assumptions suggest that between 86 and 119 Starship launches are required to deliver a single 1.44 GW SBSP system into orbit. Given current available Starship capacity (see Annex A.9), this would suggest that a single SBSP system would require between 4 and 6 years for full deployment. Launch capacity is therefore a major constraint on the delivery of SBSP at any scale.

However, given the scale of demand for launch mass that an SBSP programme would represent, it is likely that the supply of super-heavy launch services internationally will respond to this need. For example, the current US launch capacity could conceivably increase, and Europe could develop a fully sovereign super-heavy lift launch capability.

[7] Please see 'TN3 – System breakdown, costs, and technical feasibility'
[8] SpaceX's Starship User Guide indicates that a single launch can deliver 21 T to GTO. Source: https://www.spacex.com/media/starship_users_guide_v1.pdf. Frazer Nash estimate that Starship can deliver up to 29 T to orbit with each launch. This assumes that Starship is refuelled in orbit to deliver more efficient lift capability. These calculations are based on 2 Starship launches (one carrying payload the other fuel) delivering 57.9T of satellite plus the fuel needed for the OTV to get to GEO. A single Starship therefore delivers 59/2 T, or 29 T.

Clear demand signals from the SBSP design authority would therefore be required to incentive sufficient investment in global launch capacity.

3.4.6 Cost-Benefit Analysis (CBA) model assumptions

To analyse the economic costs and benefits of SBSP, an Excel-based analysis model has been created. This model captures all the costs and benefits that are monetised in this study and estimates the corresponding economic values.

The CBA uses the Net Zero scenario detailed above as the counterfactual. This implies that Europe reaches Net Zero and that SBSP therefore expediates that process. An alternative specification, where Europe fails to reach Net Zero and instead continues along a business-as-usual pathway is considered in a sensitivity analysis.

The SBSP scenario assumes a gradual deployment of Space Based Solar Power, which subsequently replaces some alternative energy sources, contributing to the European energy mix and the route to Net Zero. Relevant development costs, capital and operational costs, and potential spillovers are modelled in the scenario.

It is assumed that under the SBSP scenario, new SBSP capacity replaces terrestrial technologies utilised in the counterfactual scenario based on the demand for SBSP and constraints on the supply of SBSP.

It is expected that potential launch capacity (and also manufacturing capability) will be the most significant restricting force on the supply-side, particularly in the initial period. The intervention, or the SBSP scenario, therefore assumes gradual deployment of Solar Power Satellites to meet demand for SBSP-derived energy. Three ramp-up scenarios are modelled in the CBA:

- **Demand responsive scenario (base case)** – this scenario assumes that the supply of satellites into orbit will not be a constraint in the long-run, even if initial deployment is constrained in the short-term. The achievement of a demand-responsive supply chain seems a reasonable one in the very long-run. This is because the fixed factors of production (land, labour, capital) can be assumed to change in response to price signals over multiple decades through investment and market entry or exit. This scenario is therefore used as the base case scenario in the model and is the basis of the core results presented below.
- **US and European launch capabilities scenario (alternative case 1)** – this scenario assumes that the supply of satellites into orbit will be limited by the availability of US and European super-heavy launch capability. The supply of global super heavy launch capacity is expected to increase under this scenario in response to the scale of demand required for SBSP, but this will be limited to US and European launch capacity. However, this conservative assumption assumes that structural supply characteristics will continue to result in the undersupply of SBSP vehicles over the time period of analysis.
- **US launches only scenario (alternative case 2)** – this scenario assumes that the supply of satellites into orbit will be limited by the availability of US super-heavy launch capability and is therefore the most conservative. The supply of global super heavy launch capacity is expected to increase under this scenario in response to the scale of demand required for SBSP. However, this scenario assumes that launch will be limited to US launch capacity only and that there will be an undersupply of SBSP throughout the time period of analysis.

As detailed in Table 3-9 and Figure 3-10 0below, our base case scenario (the demand responsive scenario) assumes that the number of satellites in orbit will be constrained by the supply of satellites in orbit in short-run, but will ultimately be driven by the demand for SBSP in the long-run.

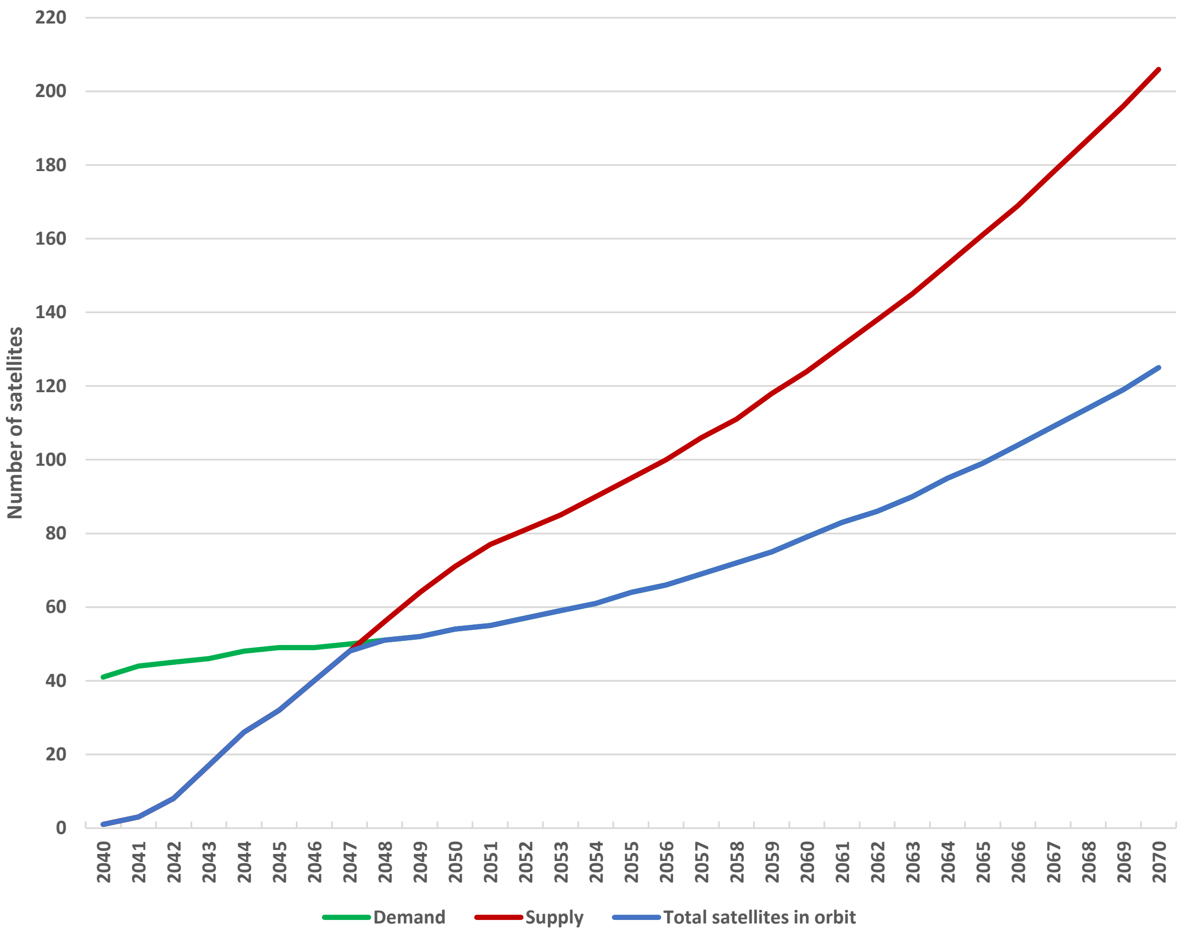
Table 3-9 Ramp-up assumptions: demand responsive scenario (base case)

Base case assumptions	Units	2040	2045	2050	2055	2060	2065	2070
Demand constraint	Satellites in orbit	41	59	54	64	79	99	125
Supply constraint	Satellites in orbit	1	32	71	95	124	161	206
Total number of satellites in orbit	**Satellites in orbit**	**1**	**32**	**54**	**64**	**79**	**99**	**125**

Note: the figures refer to the total number of satellites in orbit in each five-year interval. The difference between an interval and the one following it represents the number of new satellites to be launched between each interval.

Source: London Economics analysis

Figure 3-10 Assumptions: demand responsive scenario (base case)



Source: London Economics analysis

The model relies on a range of assumptions and date sources provided in Table 3-10.

Table 3-10 Data sources used in the model

Assumptions	Use in the model	Main data sources
Electricity generation in Europe	Build-up of the counterfactual scenario	European Union Fit for 55, International Energy Agency (IEA), International Renewable Energy Agency (IRENA), national energy policies
CO2 emissions	CO2 emissions from fuel combustion affect the environmental benefits calculations	European Union Fit for 55, International Energy Agency (IEA), national energy policies
Fuel efficiency in electricity generation	Efficiency of fuel in producing a unit of electricity combined with fuel cost affects the benefits from fuel saved calculations	International Energy Agency (IEA), US Department of Energy, UK Department for Business, Energy & Industrial Strategy, International Atomic Energy Agency
Fuel cost	Benefits from fuel costs savings	Trading economics, NASDAQ
Carbon Capture	The magnitude of CO2 emissions savings under SBSP scenario	European Union Fit for 55, International Energy Agency (IEA), national energy policies
Cost of carbon capture	The benefits of CO2 emissions savings	International Energy Agency (IEA)
Terrestrial technologies CAPEX and OPEX	Benefits from savings on direct costs of terrestrial technologies replaced	International Energy Agency (IEA), International Renewable Energy Agency (IRENA)
Load factors	Performance of terrestrial technologies, and thus, necessary investments to support forecasted electricity generation	US Energy Information Agency
Plants operational assumptions (construction time, useful lifetime, decommissioning)	Performance of terrestrial technologies, and thus, necessary investments to support forecasted electricity generation	International Energy Agency (IEA), International Renewable Energy Agency (IRENA)
SBSP assumptions	Costs and benefits of SBSP	Frazer Nash
Plant land size	Benefits of land saved	US Department of Energy
Opportunity cost of land	Benefits of land saved	European Commission

Once the evolution of the SBSP scenario is modelled, the counterfactual and SBSP scenarios are compared, and the monetised difference calculated. These values are then discounted using a 3% social discount rate to calculate present value terms.

The relevant quantified costs include all R&D costs incurred during the R&D phase of the project before construction of the prototype satellite, as well as all capital expenditure and operation & maintenance costs associated with the construction, operation, and maintenance of all satellite, rectenna, and ground control infrastructure.

Quantified benefits include:

- Benefits of avoided from Terrestrial Energy Source costs: costs related to all terrestrial electricity generation technologies, as listed above, which are avoided under the SBSP scenario, including all capital expenditure, operation & maintenance, and fuel costs.
- R&D spillovers: this includes some wider spillovers to the European industry from the Research & Development activities incurred in the development phase.

- CO2 emissions avoided: this includes the social cost of carbon (after subtracting the cost of carbon paid by companies, already included in the O&M calculations) associated with the emissions which have been avoided as SBSP displaces some fossil fuel-based technologies. This therefore reflects only the CO2 emissions produced during the fuel combustion processes.
- Opportunity cost of land: this includes the social value of land which can be used for purposes other than electricity generation, but which would have been used for energy production under the counterfactual scenario. As some technologies, namely onshore wind and solar PV (terrestrial), require vast expanses of land, this benefit can be substantial and has been quantified. For the purpose of the analysis, it is assumed that the SBSP rectenna allows for a dual use of land. For terrestrial technologies, only the cost of land in the directly affected area is considered (e.g. the land where solar PV are placed or a direct proximity of wind turbines).

3.4.7 Key findings

3.4.7.1 Monetised benefits

Under the base case the assumptions outlined above, the central estimate of net benefits of SBSP in Net Present Value terms amount to **€182.6 bn** (Table 3-11). This covers all cost and benefits attributable to SBSP over the period 2022 – 2070 and discounted at the social discount rate of 3%.

On the costs side, the Net Present Value of SBSP system costs total **€417.9 bn**. This is driven primarily by high capital expenditure, followed by operation & maintenance, and research & development costs.

On the benefits side, the Net Present Value of avoided costs attributable to terrestrial energy generation which would have to be incurred if SBSP is not pursued is equal to **€302.4 bn**. The biggest element of this is capital expenditure, followed by fuel cost, and operation & maintenance.

Added to this is the total Net Present Value of externalities which amounts to **€298.1 bn.** The biggest element is the social cost of CO2 that is avoided, which constitutes 78% of all externalities. This is followed by the quantified spillovers from R&D activities, and the opportunity cost of land.

Table 3-11 NPV of SBSP benefits: Summary

Value driver	NPV (€ billions)
(1) SBSP total cost	**(417.9)**
CAPEX (SBSP)	(382.5)
R&D (SBSP)	(10.4)
O&M (SBSP)	(24.9)
(2) Avoided cost of terrestrial electricity generation	**302.4**
(3) Externalities total	**298.1**
CO2 emissions saved	233.2
R&D spillovers	64.5
Opportunity cost of land	0.3
SBSP total benefits (total of (2)+(3))	**600.5**
Total Net Benefits (2+3-1)	**182.6**

Source: London Economics analysis

Estimates of the positive net benefits of SBSP is robust to a range of sensitivity analyses across discount rates, fossil fuel costs, social costs of carbon, and launch capacity, with estimates of net benefits falling in the range **€148.9 bn** to **€261.8 bn** in Net Present Value terms.

Even if all costs of SBSP across the board were to double, net benefits of SBSP would remain positive, at **€14.3 bn** if a smaller number of satellites were to be launched.

A separate set of sensitivity analyses (Table 3-12) is undertaken for a different counterfactual. If Europe's countries do not achieve Net Zero, but instead continue in the Business as Usual scenario (BAU), then SBSP is no longer just a means of expediting Net Zero, but instead becomes a real contributor to achieving the critical objective of Net Zero. Assuming a similar demand as in the central case, net benefits of SBSP increase substantially to **€767.4 bn**. This larger estimate is driven primarily by the greater amount of fossil fuels that are displaced under this BAU scenario.

Table 3-12 Sensitivity analysis

Sensitivity	Units	NPV of SBSP benefits
Base case scenario	€ billions	182.6
Lower social discount rate - 2.5%	€ billions	209.8
Higher social discount rate - 3.5%	€ billions	159.3
Higher fossil fuel costs	€ billions	261.8
Lower social cost of carbon - €300/tonne of CO2	€ billions	148.9
Higher social cost of carbon - €400/tonne of CO2	€ billions	215.4
Business-As-Usual scenario	€ billions	767.4
Slower SBSP ramp-up – US and European launch capability scenario (alternative 1)	€ billions	155.0
Double SBSP costs (CAPEX, OPEX, development)	€ billions	(170.8)
Double SBSP costs and slower ramp up (US and European launch capability scenario (alternative 1))	€ billions	14.3
Double SBSP costs and slower ramp up (US and European launch capability scenario (alternative 1), Business-as-usual scenario	€ billions	457.7

Source: London Economics analysis

3.4.7.2 Non-monetised costs and benefits

The green transition requires a major uplift in renewable energy generation in Europe. However, the dominant renewable energy sources, wind and solar, are weather-dependent and therefore intermittent. This will require a different way of managing the grid and ensuring there is always sufficient supply to meet demand. While storage technologies will develop and play a role, there is likely a need for a dispatchable, green, baseload technology – and nuclear power will not likely cover the need for baseload technologies by itself. SBSP is a dispatchable, green, baseload technology that can help balance the grid and reduce fluctuations in electricity supply. The benefit of this has not been explicitly monetised in this study, although the need for reduced intermittency of supply is considered in the analysis of the demand for SBSP.

Non-monetised benefits also include strategic considerations over European energy independence and specifically the current reliance on imports for fuels that SBSP could mitigate against. Other benefits to society include a better allocation of land for on-shore renewable energy generation (owing to SBSP's superior efficiency over terrestrial solar and wind), and the health benefits associated with reduced pollution.

On the cost side, the environmental impact of constructing and launching the SBSP system is a non-monetised element. Available literature suggests the impact is minor compared with the fossil fuels that can be displaced, but a firm quantification has not been performed in this study.

Furthermore, development costs of enabling technologies and services (not least European low-cost heavy-lift launch capabilities) have not been considered explicitly.

3.4.7.3 Recommendations

The report provides a range of recommendations on the next steps for SBSP, which should be considered in conjunction with the output of TN5 – Concept for a European SBSP Development Programme which is also delivered as part of the study. The recommendations include:

- Update technological feasibility studies and demonstrate technological advancement in key areas;
- Study Net Zero pathways;
- Expand understanding of SBSP's cost competitiveness;
- Evaluate non-monetised benefits;
- Study feasibility of tax and/or subsidy mechanism to encourage uptake;
- Health and safety studies;
- Public engagement and secure public buy-in;
- International engagement;
- Funding and commercialisation;
- Investigation of required hurdle rates and revision of hurdle rates over time;
- Rectenna sites and permits;
- Reinforcement of transmission network.

3.4.7.4 Study limitations

The cost benefit analysis undertaken in this study is subject to significant uncertainties owing to the long timeframe of analysis and the relative technical immaturity of the SBSP concept. The reader should note the following high-level limitations:

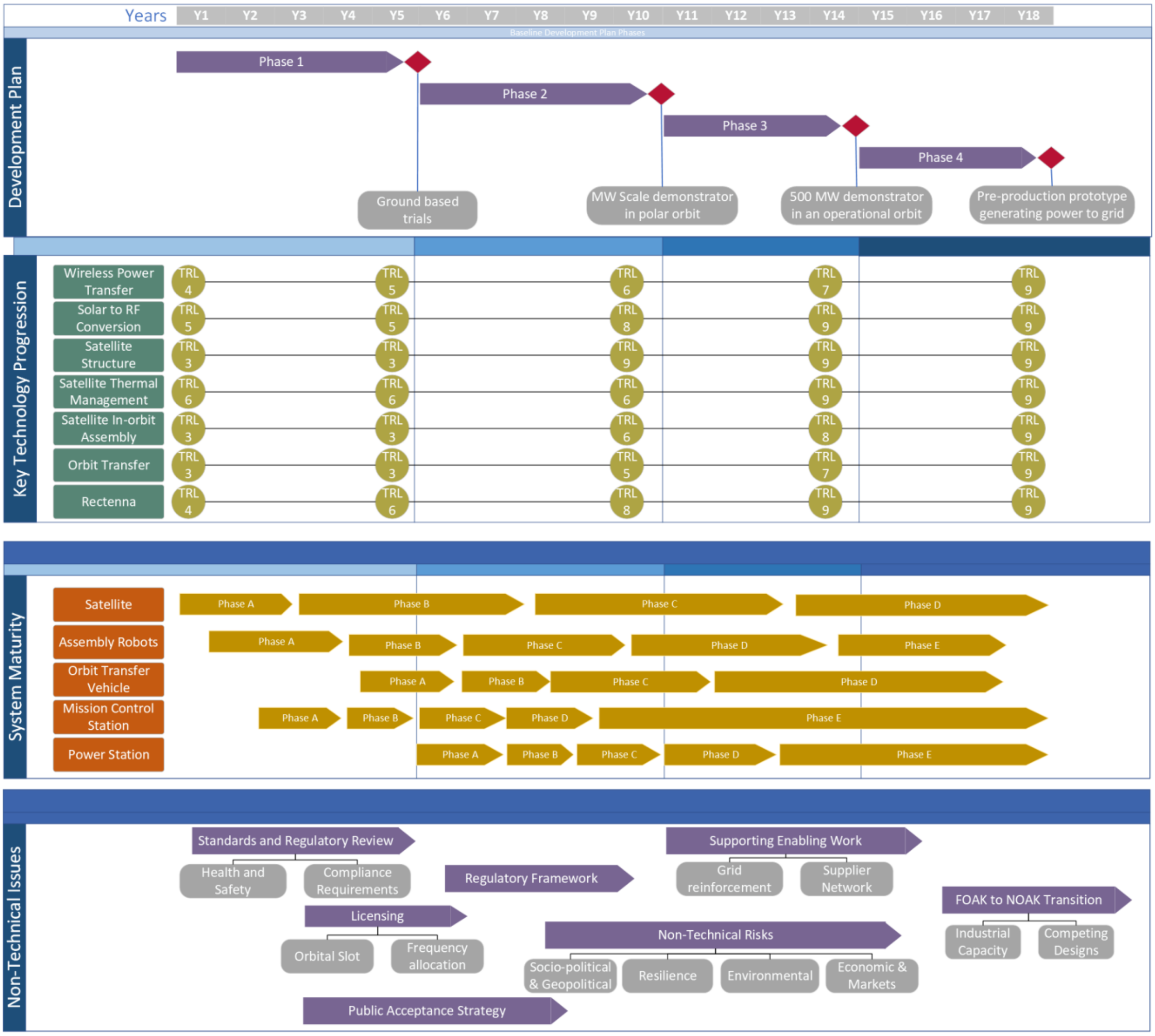
- Benefits are estimated for a new technology operating within a fast-changing energy market over a long timeframe many decades into the future. The analysis is therefore subject to a large degree of uncertainty.
- Qualitative variables are difficult to quantify.
- The benefits potential of SBSP is ultimately tied to government policy decisions.
- There remains uncertainty about the precise nature of the SBSP system and its development.
- The landscape for energy technologies is changing rapidly and any development could change the comparative attractiveness of SBSP.
- Demand forecasts for technologies with SBSP's characteristics and for electricity in general are uncertain.
- Forward-looking LCOE and VALCOE estimates rely on many assumptions. Although these are sourced from reputable organisations such as the IEA, the veracity of the assumptions cannot be verified this many years in advance.
- While the economic analysis contained in this report represents industry best practice, the costs and benefits assessed are not assumed to be exhaustive. For example, the environmental costs of constructing an SBSP system, though marginal compared to fossil fuel externalities, are not included.
- The study does not purport to present a comprehensive assessment of and recommendation on Europe's energy policy beyond SBSP. It also does not consider any general equilibrium effects arising from build and launch of a large volume of mass into space in terms of raw materials and service costs.

3.5 A European SPS Development Roadmap

Figure 3-11 presents a four-stage development programme structured in a sequence designed to mature the technologies needed for the SBSP system, through a series of increasingly large and complex prototypes to develop the design of the system, leading to a full-scale pre-production operational prototype. It illustrates pace of development of the underpinning technologies, the maturity progression of the key systems across the four phases (development testing, initial in-orbit demonstrations, full system in-orbit demonstrations, production level scale-up) and highlights where some of the non-technical aspects will need to be tackled. It includes major milestones, such as in-orbit demonstrators and technology progression.

The four-phase development programme presented is just one example of a possible development approach. The programme is aims to achieve a balanced risk profile through the development stages by incremental development of the key elements of the system. A description of each phase follows.

Figure 3-11 Outline Development Plan



Phase 1 – Development testing

The first phase of the development plan focusses on two areas of development testing: wireless power transmission and photovoltaic conversion efficiency. The wireless power transmission developments will use ground-based trials to successively increase the distances over which power can be reliably and safely transmitted considering the effects of the environment and on the environment. As well as developing the key elements of the satellite radio frequency (RF) modules these trials will also establish the key characteristics of the rectenna modules. Going into space is a significant step in the development programme and the costs increase significantly. Delivering the hardware into orbit, conducting development modifications and returning the hardware for inspection are far more complicated in space than on the ground, therefore ground based trials will be used where possible. The photovoltaic conversion efficiency developments will use lab-based tests to optimise the design of the optical elements and the packaging of the cell. In parallel with these demonstration trials, the systems that will be trialled in the subsequent stages will be designed.

Phase 2 – Initial in-orbit demonstrations

The second phase centres around in-orbit demonstrations. This will involve a solar power satellite and associated systems that can be placed in orbit with a single spacelift. The choice of orbit will be a balance between size of the satellite and the residence time over the ground station. Higher orbits have longer orbit periods and hence longer residence times over a ground station, however the longer beaming distance from higher orbits mean that the satellite needs to be larger to deliver meaningful energy density at the ground. This satellite will be based on the architectural elements of the operational satellite but will use conventional self-deployment mechanisms and so does not require the autonomous assembly robots. This satellite will not be mass optimised to the extent that later satellites will need to demonstrate. It will use conventional self-deployment mechanisms to erect the satellite in orbit. The key focus of the in-orbit trials in this phase is to further de-risk the wireless power transmission elements and explore the characteristics of the satellite modules in a space environment. It will draw upon conventional satellite systems where necessary. In parallel with the in-orbit trials the design of the orbit transfer vehicle and the autonomous assembly robots will be completed, supported by suitable ground-based investigations.

Phase 3 – Full system in-orbit demonstration

The third phase brings all the key elements of the system together into an in-orbit demonstrator that includes all the elements of the operational system. It will operate from an intermediate elliptical orbit and will use the autonomous assembly robot. The key focus of this stage is to prove the elements of the system that allow the hyper-modular satellite to be delivered and constructed. This includes the packaging of the modules for spacelift and their deployment in-orbit, autonomous in-orbit assembly and optimisation of the module interfaces for dependable assembly. There will also be the opportunity to further refine the wireless power transmission performance and photovoltaic efficiency.

Phase 4 – Production level scale-up

The fourth phase involves scale-up of the elements to a full production size operational system in a geostationary orbit. This will involve proving the capability of the orbit transfer vehicle as presenting the opportunity to further refine the other elements of the system.

3.5.1 Sub-System Development Pathways

To progress through the development phases a series of sub-system developments must take place. A sub-system development pathway is presented in Figure 3-12, which builds on the technical maturity assessment presented in Section 3.2.3. It shows the required TRL development for each sub-system. A high-level description of the primary considerations for each sub-system follows. A detailed description of the underlying development philosophy for each of the sub-systems is presented in Annex

Figure 3-12 Sub-system Development Paths

			Phase	1					2					3				4			
		Subsystems	**Year**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Core Power Systems	Satellite	Satellite collect	TRL5														TRL8				TRL9
		Satellite convert	TRL6										TRL7				TRL9				
		Satellite transmit	TRL4					TRL5					TRL6				TRL7				TRL9
		Satellite structure	TRL3					TRL3					TRL5				TRL8				TRL9
		Satellite thermal management	TRL6										TRL6				TRL9				
		Satellite control system	TRL4										TRL5				TRL7				TRL9
		Satellite station keeping	TRL3										TRL4				TRL7				TRL9
		Satellite communications	TRL6										TRL7				TRL9				
	Ground Stations	Ground receive	TRL4					TRL6									TRL9				
		Ground convert	TRL7														TRL9				
		Ground distribute	TRL7														TRL9				
		Ground grid connection	TRL8														TRL8		TRL9		
		Ground structure	TRL7														TRL9				
		Ground control system	TRL6										TRL8				TRL9				
		Ground Operations: Power Control Interface	TRL8														TRL8		TRL9		
		Satellite operation: Mission Control Interface	TRL5										TRL8				TRL9				
		Ground communications	TRL4					TRL5					TRL7				TRL8				TRL9
Enabling Systems	Satellite	Spacelift	TRL7												TRL8				TRL9		
		Satellite component/module manufacture	TRL6										TRL8		TRL9						
		In-orbit assembly	TRL3								TRL4		TRL6		TRL8		TRL9				
		In-Orbit maintenance	TRL3								TRL4		TRL6		TRL8		TRL9				
		Decommission satellite	TRL2																		TRL7
	Ground Stations	Rectenna manufacture	TRL4														TRL8				TRL9
		Power station construction	TRL8																		TRL9
		Operation Station construction	TRL8																		TRL9
		Maintenance of Ground Stations	TRL7																		TRL8
		Decommission Ground Stations	TRL8																		TRL8

Maturing the satellite and its subsystems is the primary focus of the development programme. Through the phases of the development programme, the demonstration satellites increase in size and the power beaming distance increases. The satellite design is hyper-modular; it is made of a very large quantity of a small number of different modules. The satellite has not been designed yet, but it is anticipated that there will be between 5 and 10 different modules within the satellite. Each module within the core of the satellite will contain all the functionality to receive solar insolation along with the retrodirective pilot beam and a phase reference to generate microwaves as part of a coherent transmission beam. The modules will communicate with each other and be mechanically interconnected to provide the structure of the satellite core using features to enable autonomous robotic assembly and maintenance.

The development of the functional performance of the core modules will start in Development Phase 1, with ground tests of the wireless power transmission and integration of the photovoltaics. By the end of Development Phase 2 the convert and transmit functionality of the core modules will have been demonstrated. Development Phase 3 will allow the autonomous assembly features to the core modules to be tested, and their performance to be enhanced. Development Phase 4 provides the opportunity for the full end to end performance at full scale to be tested.

The development of the mirror modules and the associated support structure will lag behind the core modules. The mirror system used on the demonstration satellite in Development Phase 2 will be self-deploying without the use of autonomous assembly. Therefore, while it may use elements of the mirror modules it will employ systems that are not going to be part of the final operational system. However, there will be the opportunity during Development Phase 2 to carry out ground trials of the mirror and support structure modules and hence de-risk these elements before the in-orbit demonstrations as part of Development Phase 3. Throughout the development phases appropriate use will be made of engineering analysis, systems engineering and digital twins. The underlying development philosophy for each of the subsystems is presented in Annex A.8.

Potential to Reduce the Development Timeline

The duration of the development phases presented in Figure 3-12 are based on engineering judgement of the pace at which the milestones could be achieved. Given that the introduction of SBSP will be driven by the imperative to tackle the climate emergency and deliver a significant contribution to Net Zero, there will be pressure to shorten the development timelines as much as possible.

Fundamentally the development timeline is governed by the development of the satellite. In turn, the satellite development is dependent on the ability to prove that wireless power transmission can be delivered safely, controlled effectively and at acceptable levels of efficiency from GEO through space and the layers of the atmosphere. All other development aspects are independent from each other and can be delivered in parallel, reducing the overall development timeline. Therefore, there are three fundamental strategies that could be considered to reduce the development timeline, from 18 years, to approximately 14 years. They are:

1. Concertina each development phase by deploying more resources.
2. Remove development phase 3 and complete all the remaining development in Geostationary Orbit.
3. Undertake more extensive ground-based trials for the development of wireless power transmission, extend development phase 1, remove development phase 2 and rely on development phase 3 to de-risk the wireless power transmission elements.

A successful development programme will be signalled through the achievement of several key performance indicators (KPI). As the roadmap matures, targeted values should be developed to monitor progress. Several KPIs are suggested in TN5 [5]. They include:

- **Financial** measures to enable comparison with other forms of energy generation and to measure economic performance representing the balance between system costs and value of energy generated. Monitoring the true value of financial metrics referred to in elsewhere in the report, such as LCOE and NPV and IRR will be important.

- **Systemic** performance metrics should be monitored as part of ongoing system performance reviews. Targets should be get for power output (grid capacity and total energy generated), as well as service interruptions.

- **Environmental** metrics that should be monitored include the greenhouse gas emissions from manufacture and operation versus CO_2 emissions avoided. Other factors such as biodiversity and the impact of microwave exposure should also be monitored.

- **Technical** measurements will be critical in determining the overall success of the SBSP system. In particular, the energy chain efficiencies achieved will need to be closely monitored to ensure expected performance parameters can be met to make the overall system efficient. The reliance of the technology on space-lift means that factors affecting space-lift costs should be closely monitored.

3.6 The Scale of a European SBSP Solution

Demand for SBSP

In TN4 [4], and noted in Section 3.4.5 the scale of the European SBSP intervention is defined by estimates of the theoretical maximum demand for SBSP as a function of SBSP's Value-Adjusted Levelised Cost of Electricity (VALCOE), dispatchability, and renewable nature. However, there are a number of supply constraints discussed below, that will affect the build rate of a European SBSP capability. These constraints suggest a gradual scaling of the system and limits to the overall scale.

As indicated in the development plan, the first prototype satellite can be placed in orbit after the development phases are completed (assuming technical development barriers are overcome), with new satellites placed in orbit after two years. Further, as demonstrated in TN4 and referred to above, land availability should not be a significant constraint, and neither should industrial capacity given the long lead-in time for the economy to adjust (assuming a SBSP development programme and sufficient accompanying market support or signal). The primary constraint therefore is launch capacity. Consequently, the analysis of the costs and benefits in TN4 and the commercialisation options that follow are based on three scenarios characterised as follows.

- Demand driven
- US and European launch capabilities
- US launches only

Under the demand driven scenario, the number of satellites will be driven by the demand for SBSP as described in TN4. Initially, the number of satellites will be limited and the ramp up will increase to bring the total number of satellites to the demand-driven potential.

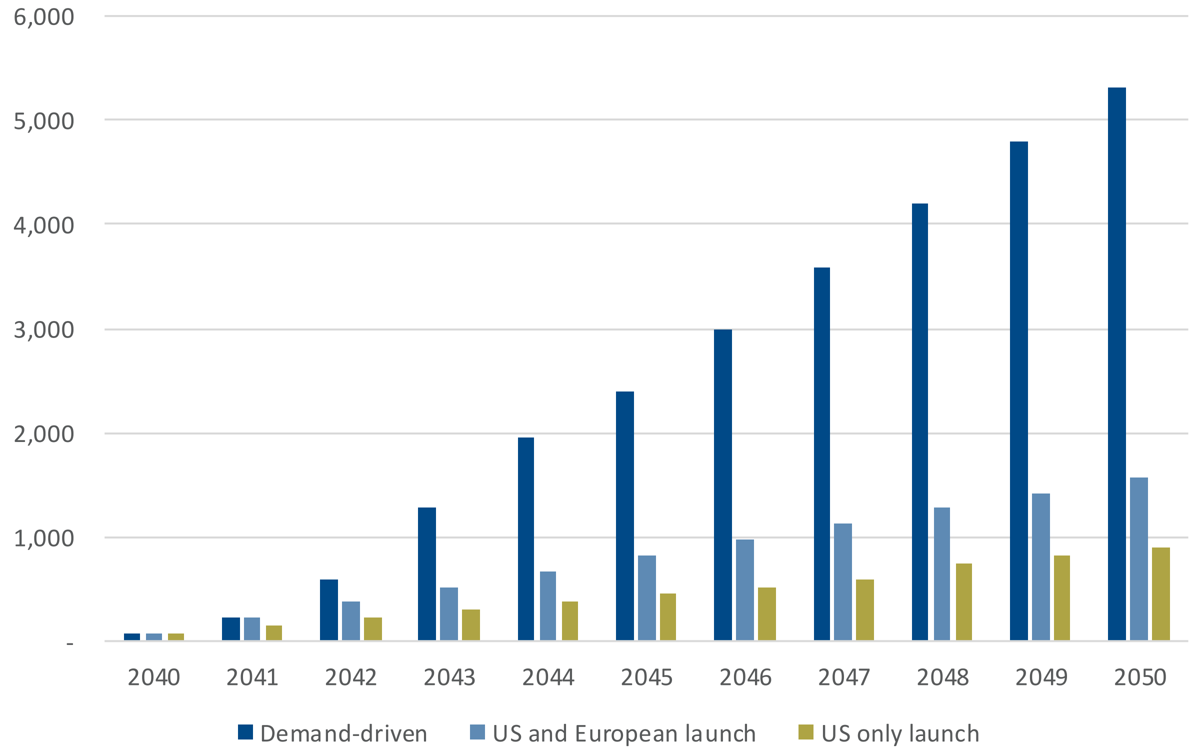
Table 3-13 Demand Scenarios for a European SBSP up to 2070

Assumptions	Units	2040	2045	2050	2055	2060	2065	2070
Demand-driven	Satellites	1	32	71	95	124	161	206
US and European launch	Satellites	1	11	21	31	41	51	61
US only launch	Satellites	1	6	12	17	22	27	32

Under a more conservative scenario, the total number of satellites will be limited by the existence of US and European launch capabilities. This scenario reflects improvements to both existing US super-heavy launch capacity, and the arrival of a sovereign capability to service Europe's strategic needs. Finally, the most conservative scenario assumes that the total capacity of the SBSP system will be fully limited to improvements in existing US launch capacities only, whether from SpaceX's Starship, Blue Origin, or others. The resultant build rates for each scenario are shown in Table 3-13

Assuming a launch capacity of 26.7 tonnes as recorded by Space X for their Starship rocket, the number of launches per year can be inferred based on the number of satellites and their expected mass. Section 3.7 documents the findings of a study into the commercialisation options for these scenarios.

Figure 3-13 Cumulative Launches under different scenario build rates up to 2050



Supply Constraints

There are a number of supply constraints that will limit the supply of a European SBSP capability. These supply constraints can be classified as follows:

- **Launch capacity** -limitations to the potential cadence of satellite launches to deliver the SBSP system into orbit, given limited launch service capacity.
- **Cost and financing** - delays to or failure to finance the large capital requirements of the programme.
- **Technological development** – failure of the development programme given the low maturity of SBSP subsystems.
- **Geographic barriers** - limitations to the siting of rectennas given their large geographic footprint
- **System build rate**- limitations to build rate, given its technical complexity and the large scale of industrial requirement that it implies, and
- **Other factors**: political, regulatory, and legal constraints.

The system build rate is determined by the achievement of key technological developments in enabling technologies, and the capacity of the industrial base to deliver and launch SBSP modules into space. The research performed in this study considered there factors of production to assess industrial capacity. They are land, labour and capital.

- **Land** – the siting of rectennas is challenged the limited available of unrestricted land which can accommodate the large size of rectennas, although they can also be sited offshore. There is also potential for dual use of a rectenna location, subject to microwave safety, which could significantly reduce the costs and land impact. A simple geographic information system (GIS) analysis was performed as part of the study to infer the likely availability of sites, accounting for settlements, roads and protected land. It concluded that in all five of the top European emitters there was sufficient locations to explore rectenna siting such that land should not be a constraint.
- **Labour** - the space sector is home to highly skilled professionals around the world, such as technicians, scientists, and engineers, with other ancillary professions ever more represented (e.g., business, legal). Space-related employment includes jobs in public administrations with responsibilities for managing space activities and publicly funded research and development programmes (space agencies, space departments in civil and defence-related organisations), the core space manufacturing industry (building rockets, satellites, ground systems), direct suppliers to this industry and the wider space services sector (commercial satellite telecommunications). A review of the labour requirement for SBSP, and the existing industry labour composition reveals that there should be sufficient labour to meet demand, subject to competition from other sectors and sufficient upskilling for key elements such as assembly, integration and test, which are likely to be labour intensive.
- **Capital** - access to capital from private investors for a successful SBSP project requires that investors are ensured of a risk adjusted return, given the level of uncertainty inherent in the programme. Delivery of SBSP satellites beyond a publicly funded FOAK requires substantial capital to be delivered by private investors. Decisions to invest are taken at the firm-level and firms need appropriate incentives or a degree of certainty in future returns to commit capital. The role of government in this context is not necessarily to provide these incentives directly but may be to ensure that the market is appropriately structured, such that these incentives exist, perhaps through signals that firms have from government, or from government providing confidence in the coordination of the programme that there will be a return from the investments. In this way, market failure can be avoided, giving investors' confidence they will be able to recoup investment at a tolerable level of risks.

Other constraints to the build rate and timescales for SBSP in the form of socio-political, regulatory, and legal restrictions. Public acceptance is a key constraint that must be carefully managed. The location of onshore (and to a lesser degree, offshore) rectennas is likely to come under threat from the resistance of local residents and campaign groups. NIMBYism could pose a substantial threat to the location of rectennas. The success of the demonstration satellite is vital in creating the right market signals to attract investment. On the regulatory side, it will be essential to obtain frequency and orbital rights to allow the satellite to operate in-orbit and to allow the microwave beam to transmit the energy back to Earth. Legal issues around the precise nature of the microwave transmission will have to be overcome. Planning permission for rectennas and other legal barriers could pose a risk to the success of the programme.

To overcome these constraints and obtain the substantial benefits that are associated with the delivery of SBSP at scale, major government intervention is required. Specifically:

- **Technology scrutiny and R&D effort** is required given the generally low maturity of SPS sub-systems. This is dependent on having a clear understanding of the development route that maximises outcomes whilst minimising developmental risks, and engagement from the private sector with its capacity for risk and innovation.
- **Financing** - SBSP at scale is expected to be extremely capital intensive. This burden is beyond the resources of fiscally constrained government, so private sector sources of capital will be required to plug the financing gap. However, the high upfront investment profile, long development timelines, technical

risk, and regulatory barriers, means that the availability and cost of private sector capital may be prohibitive in the short-term. Government involvement to de-risk SBSP technology and demonstrate a feasible business model as soon as possible may encourage private sector to engage in the programme and provide capital to scale the SBSP concept.

- **Investment in multiple sectors**, such as satellite and PV array manufacturing and heavy space launch services, is also required to build the industrial capacity to deliver SBSP at scale. The private sector will only make these investments if they have confidence in the technical and commercial viability of the SBSP concept, or if governments send clear demand signals to industry to de-risk investments. Larger scale investments (whose costs may not be easy to amortise across an SBSP delivery programme) may require direct government financing, coordination and/or formalised customer commitments to secure financing.

The delivery of SBSP requires early engagement from the private sector (as a source of capital and innovative capacity), but this can only happen if it is preceded by efforts to de-risk the technology and demonstrate that it is both technically and commercially feasible. This suggests that SBSP's development programme should frontload public sector resources to deliver a successful pilot and early demonstrator programme as soon as possible. Since a large source of SBSP benefits are related to its roles in displacing the carbon emissions from non-renewable sources of energy, the economic return to SBSP will reduce as the operational date for SBSP is delayed and/or the ramp-up rate is reduced.

3.7 Commercialisation Options

SBSP is a novel concept for a potential energy generating infrastructure that has many features of a modern utility, including:

- Large upfront capital expenditure (CAPEX) in the rough order of magnitude (ROM) of € billions.
- Supply of an essential service (electricity) for end users, including consumers, businesses, and government.
- A comparatively long asset lifetime, suggesting service delivery for >15 years, which could be extended further given the modularity of the system and option to replenish it with newer generation subsystems.
- Long-term and stable revenue-generating potential from the provision of capacity, power, and ancillary services through competitive market trading or long-term contracts (Power Purchase Agreements).
- Sharing the characteristics of strategic asset whose continuity is important from the government's perspective and suggesting a role for government in the market for the asset's service (just like other Critical National Infrastructure).

Infrastructures with these characteristics are attractive to the private sector. This is beneficial from a programme perspective as the participation of the private sector can offer several advantages to the financing, delivery, and operation of SBSP, including:

- Transfer of risk from the public to private sector.
- Offering a new source of capital with the potential for a risk-adjusted return.
- Provision of an additional layer of rigour given the need for independent scrutiny and due diligence on everything from contractual arrangements to technical design.
- Providing a source of technological innovation in the design and build phase.
- Providing the capabilities to support the construction of the system.

- Supporting efficient operations, management, and decommissioning of the asset.

Considering the significant capital requirement and level of technical innovation required to deliver SBSP at the scale needed to deliver some of the key economic, environmental, strategic, and social benefits outlined in TN4, it is clear that private sector participation will be critical to the delivery of SBSP.

Nevertheless, there are a large number of different models for involving the private sector in an infrastructure programme like SBSP. Each model implies different levels of ownership, risk, responsibilities, and requirements. To simplify analysis, these models can be abstracted into three classifications of public-private involvement:

- **Government-Owned Government-Operated (GOGO)** systems, such as service contracts.
- **Government-Owned Contractor-Operated (GOCO)** systems, such as management contracts and lease models and under some circumstances concessions and build-operate transfer models.
- **Contractor-Owned Contractor-Operated (COCO)** systems, such as privatisation and under some circumstances concessions and build-operate transfer models.

A simple reading of these models would suggest that only the timing and degree of private sector involvement vary between them. However, SBSP itself is an infrastructure comprised of several different elements—each with their own functional characteristics, including a space segment, a ground control segment, an SBSP power station segment, and a grid network interface. This suggests another dimension that complicates any analysis on the suitability of different commercial models for SBSP. In order to evaluate the viability of these different options the potential financial and economic costs and benefits (and therefore incentives) across the whole value chain and for all market participants was assessed. The output of this research is summarised in Table 3-14.

Table 3-14 Summary of commercialisation options for a European SBSP

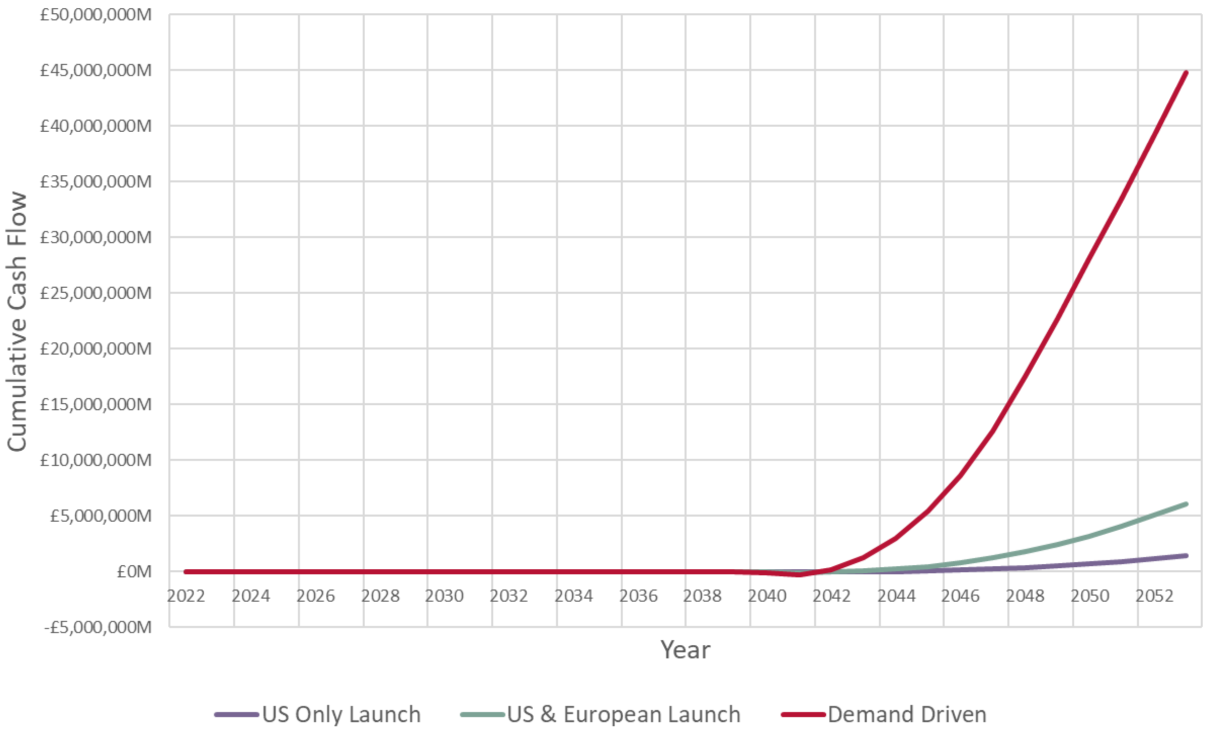
Category	GOGO	COCO	GOCO
Asset Ownership	Gov	Contractor	Gov
Intellectual Property Ownership	Gov	Contractor	Contractor
Asset Ownership	Gov	Contractor, with oversight	Contractor
Personnel	Gov	High	Contractor
Competitive Efficiency	Low	High	Medium
Price Efficiency	High costs	Low costs	High development costs, low operational costs
Strategic Planning	Gov	Contractor	Gov/Contractor jointly
Private Sector Requisite Risk Appetite	N/A	High	Low

Financing a European SBSP

The challenges of funding a new energy generation technology which is characterised by high up-front capital costs and a significant development programme which carries technical delivery risk, followed by back-ended financial payback were noted in Section 3.6. This section of the analysis focusses on defining the scales of the financing challenge. It provides an assessment of the costs for the three demand scenarios noted above. Then, it considers the financial costs to overcome the 'hurdle' rate for the development of the FOAK. In doing so it provides insight into the optimal combination of public and private sector contribution to realise a European SPS.

An assessment of the whole system cumulative under the different scenarios shows that the flow of cash will become positive as the satellites start generating electricity which is sold to the European grid by 2043 for the US launch and US and European Launch scenario, and 2042 for the demand driven scenario. In the scenario which considers a US launch capability only, the project becomes cash positive in 2045 (Figure 3-14 Cumulative Cash flow for a European SBSP system – Scenario Analysis

Figure 3-14 Cumulative Cash flow for a European SBSP system – Scenario Analysis



The analysis illustrates the significant revenues that could be received from a European SBSP—but not without risky investment to pay for the up-front costs of the development programme and associated delivery risks. Therefore, there is a clear challenge of financing the early stages of development. The study explored this challenge by modelling the impact of public sector investments to mitigate some of the development 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. The analysis predicts estimates of the return on investment and payback period for the development programme, and FOAK costs, using the expected level of energy production and costs derived in TN3, and then draws on examples of other large-scale energy project funding mechanisms and capital costs.

The internal rate of return and net present value figures were calculated without European government and/or public institution funding. They show that if a private company or private finance vehicle were to wholly fund the development of an FOAK SBSP 1.44 GW system, there is a high risk that the internal rate of return does not exceed a high hurdle rate of 20%. As a result, the incentive to invest is likely to be low given the risk of losses and the extremely high payback period. To address the likely financing gap public financing is likely to be required. Figure 3-15 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 58 percent of the costs through this mechanism. Any higher than that proportion, the incremental increase in grant could result in deadweight and displacement. If the hurdle rate was 15% then a public sector contribution of approximately 30% would be required, reflecting the lower risk and thus greater private sector interest in investing early in the programme.

Figure 3-15 Public Funding Thresholds based on p50 cost estimate values

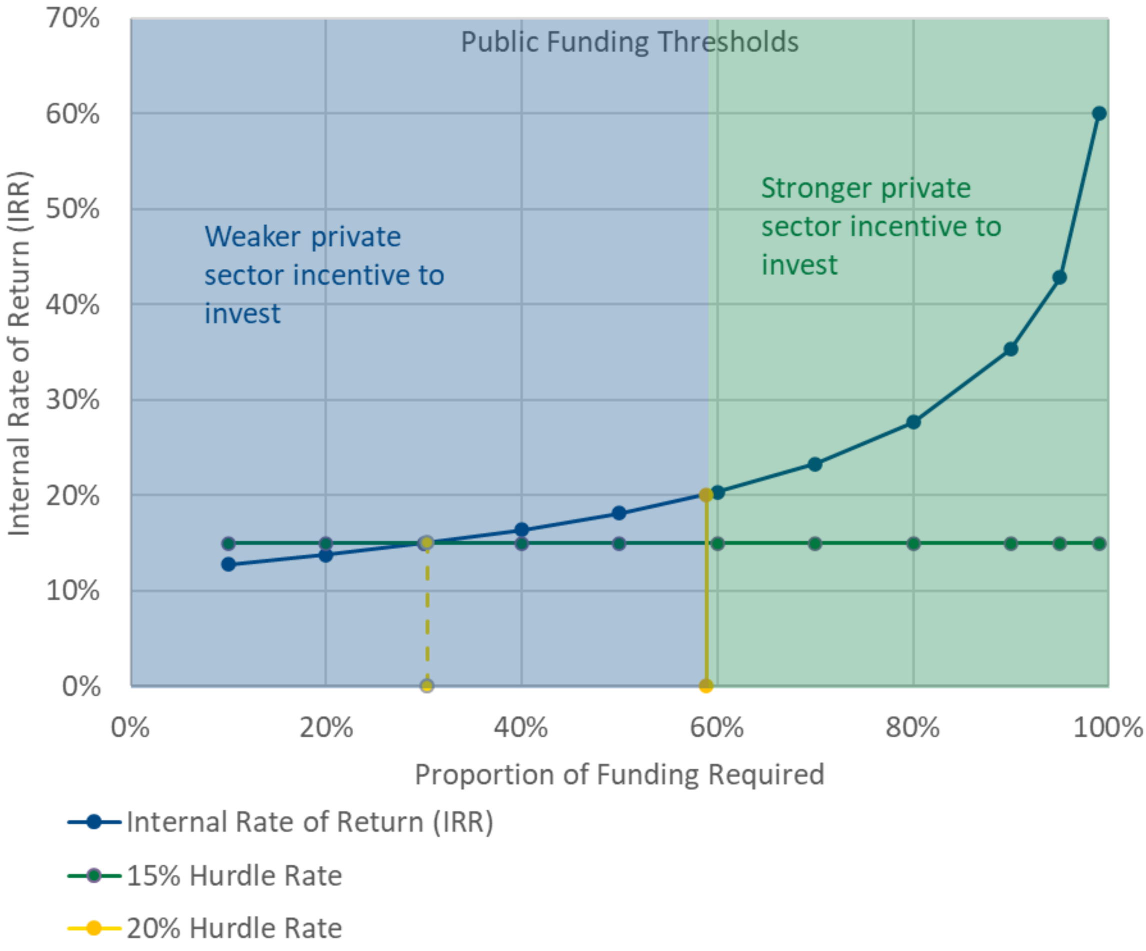


Table 3-15 and Table 3-16Figure 3-15 display potential private and public funding streams to fund the development across the four phases in view of the public funding thresholds analysis for varying hurdle rates. The financial cost of SBSP to the public sector could reach €6 billion and with €4 billion co-leveraged from the private sector. The main entry point for private funding is assumed to be during phase 2, coinciding with the completion of the first in-orbit MW-scale demo, showing the technical and potential economic feasibility of the system, which will reduce the risk perception substantially to private investors and companies.

With a hurdle rate of 15%, the central government grant becomes 30% of total costs as the level of risk perceived to the private sector is less assuming a successful demonstrator programme. Therefore, the total cost costs of to the public sector across the four phases is circa. €3 billion with a requirement of co-leveraged private investor funds of circa. €7 billion. Therefore, a reduction in perceived risk and high cost of capital has a significant effect on the public/private sector funding split.

Table 3-15 Public/Private Funding Split for Development (p50 values) with a 20% hurdle rate

Phase	Phase 1: TRL6	Phase 2: TRL7	Phase 3: TRL8	Phase 4: TRL9	Total
Public Funding %	100.0%	80.0%	70%	52%	
Public Funding Contribution	€140M	€480M	€1,876M	€3,495M	€5,991M
Private Finance Contribution	€0M	€120M	€804M	€3,260M	€4,184M

Table 3-16 Public/Private Funding Split for Development (p50 values) with a 15% Hurdle Rate

Phase	Phase 1: TRL6	Phase 2: TRL7	Phase 3: TRL8	Phase 4: TRL9	Total
Public Funding %	100.0%	50.0%	30%	27%	
Public Funding Contribution	€140M	€300M	€804M	€1,848M	€3,092M
Private Finance Contribution	€0M	€300M	€1,876M	€4,907M	€7,083M

An alternative methodology to explore the funding mechanisms would be for the ESA and its key Member States 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 3-17 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%.

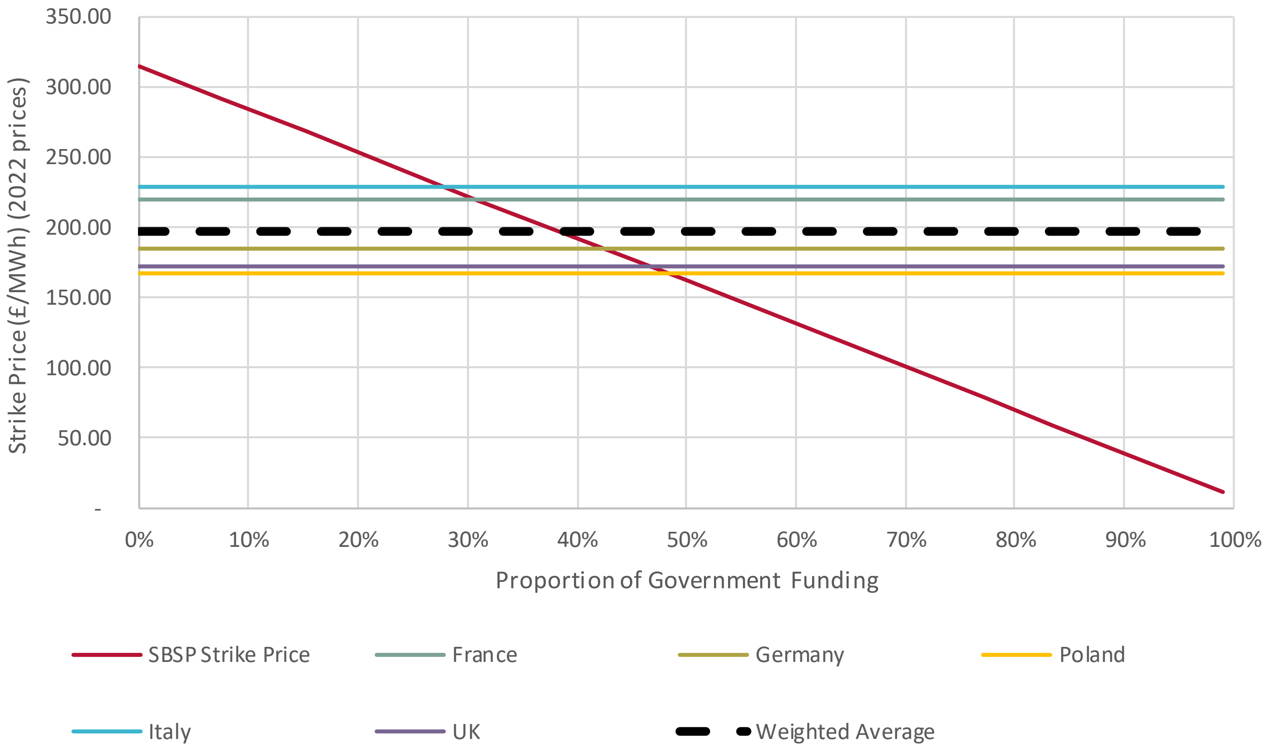
Table 3-17 Setting a Public Sector Budget Constraint and Determining the Strike Price of Energy for the FOAK SBSP System (€ millions rounded to nearest million)

Government Budget	Proportion of Public Funding	Strike Price (€/MW) (2022 prices)	Hurdle Rate	Private Contributions
€1,900M	15%	271.16	20%	€11,200M
€2,200M	17%	264.14	20%	€10,900M
€2,600M	20%	254.68	20%	€10,500M
€4,400M	34%	211.37	20%	€8,700M
€6,500M	50%	163.32	20%	€6,600M
€8,200M	63%	123.39	20%	€4,900M
€10,100M	77%	78.55	20%	€3,000M
€10,900M	83%	59.82	20%	€2,200M

€13,100M	99%	11.72	20%	€100M

This analysis helps to identify at each given government funding level, how price competitive SBSP could be relative to other electricity generating technologies' strike prices. The value (euro/MWh) of electricity was gathered on the five European countries EEX Power Future's market data. This data shows how much buyers, recently, are willing to pay for energy at a predetermined future delivery date across the five countries in this study along with a calculated weighted-average future price for electricity (weighting by country-specific energy demand). It suggests a public sector contribution for the development R&D in the region of 40%, so that SBSP can be price competitive.

Figure 3-16 Strike Price of SBSP for a Given Proportion of Public Funding for SBSP R&D Compared to Future Settlement Price of Electricity by European Country



Annex A - Supporting Documentation

A.1 Cost Assumptions

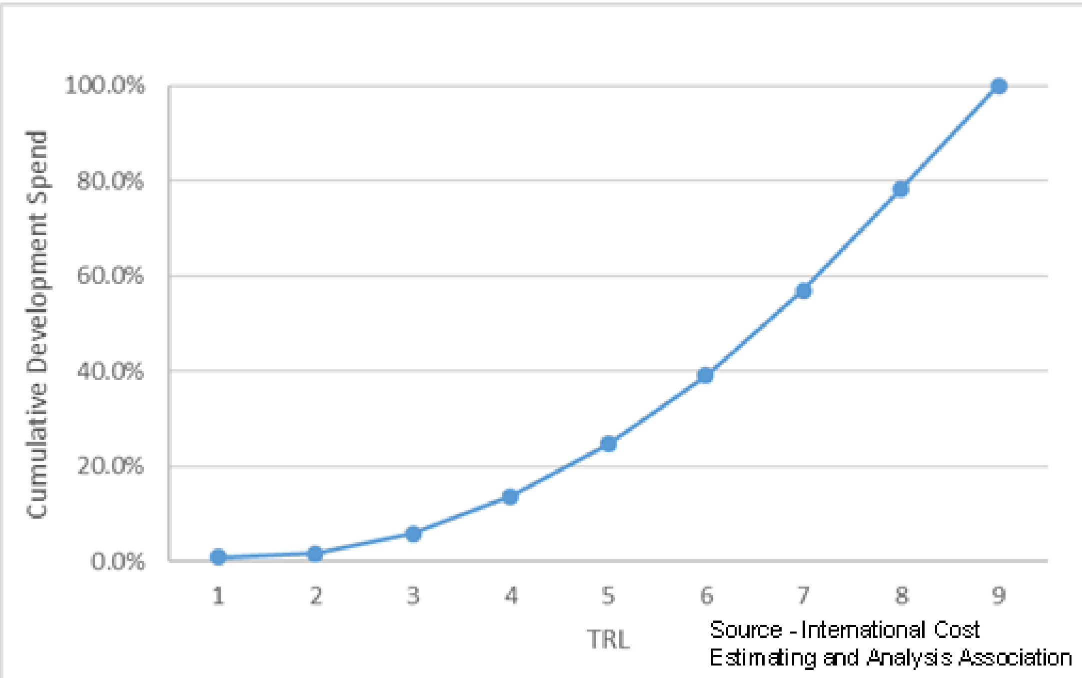
Item	Assumption Detail
Satellite life	The life of the satellite is assumed to be 30 years. This is longer than the typical life of current space assets. However, there are economic and environmental pressures to extend the life of all space assets. SBSP systems will be able to capitalise on these advances in the future. The model degrades the satellite power output over its life, which is taken into account in the yield calculation and therefore the LCOE.
Photovoltaics	The solar collector uses space rated triple junction high concentration photovoltaics with Fresnel primary and Köhler secondary optics.
Spacelift	Launch operators typically publish their capacity to a geostationary transfer orbit and this has been used to infer the payload that could be delivered with in-orbit refuelling. Launch costs have been inferred from current costs. A dedicated orbit transfer vehicle will be used to deliver the payload to the final orbit.
In-orbit station keeping	There are several options to minimise the need for in-orbit station keeping propellant by using geostationary orbits and utilising photon pressure on the mirrors to control attitude. However, to reduce the development burden and associated uncertainty the system uses a more conventional approach; ion thrusters to provide the delta-V to maintain a geostationary orbit and move the satellite into a graveyard orbit at end of life.
Maintenance and re-supply	It is to be expected that a fully developed system will have a comprehensive maintenance and resupply programme. However, in the absence of any information on how this will be achieved the costing assumption is that all the hardware and propellent necessary for its whole life is delivered at the beginning of life. A factor is then applied to represent the degradation in performance over its life.
Construction duration	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. 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.
Decommissioning	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.
Cost of finance	A 20% discount rate is used for discounting in the calculation of LCOE. The discount rate is used to account for the costs of capital and risks in the project is based on the projected

Item	Assumption Detail
	hurdle rate required by institutional investors. This discount rate is similar to that used for other low maturity systems.
R&D costs	The CAPEX, OPEX and LCOE cost calculations assume that the necessary research, development, test, and evaluation has been completed before the systems are produced and therefore don't include any of these costs. A separate estimate of the R&D costs is provided. This is based on the capital cost of each sub-system and the phase in which that sub-system is first 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.
Development programme - spacelift	The development programme includes costs for the development of a bespoke orbit transfer vehicle.

A.2 Approach to estimating development costs

There are a number of ways that the costs for a programme of this type can be estimated, ranging from benchmarking against similar programmes at one extreme, to detailed bottom-up costing at the other. The approach that has been applied here sits between these two extremes, and uses the following structure:

- Establish the cost breakdown of the operational grid connected system, using capital expenditure (CAPEX) and operational expenditure (OPEX) outputs from the cost model.
- Identify the system elements that require significant development and calculate the cost of the associated research, development, test and evaluation (RDT&E) by factoring the hardware costs by 5.5, based on established metrics published by Wertz in Space Mission Analysis and Design [19]. The key system elements that require development are: the satellite, the assembly robots, the orbit transfer vehicle and the rectenna.
- Apportion the hardware development costs of each system element over the relevant phases of the development plan, based on development spend distributions from the International Cost Estimating and Analysis Association [20] as illustrated below.
- Use the cost breakdown structure and associated metrics to calculate the cost of the supporting systems and the systems engineering necessary to provide a framework for the development.
- Sum the cost elements for each phase of the development



Rate of Development Spend against Technical Maturity Level (TRL)

As there is significant uncertainty in the costs, we have provided a three-point cost estimate, at low (p10) medium (p50) and high (p90) probability.

A.3 List of organisations represented at stakeholder workshops

BP
Breakthrough Energy
Climate-KIC
Equinor
European Space Agency
Frazer-Nash
Imperial College London
International Electric Company
International Energy Agency
London Economics
OHB
Roland Berger
Shell
Thales Alenia Space
The Department for Business, Energy and Industrial Strategy
The World Economic Forum
University of Aveiro
University of Glasgow

A.4 List of research papers reviewed as part of Task 1

Ref	Title
RD 1	ESA Agenda 2025
RD 2.1	Legal Aspects of SPS (2021)
RD 2.2	SPS for space applications (2004)
RD 2.3	Roles of Solar Power from Space for Europe: Space Exploration and Combinations with Terrestrial Solar Power Plant Concepts (2004)
RD 2.4	Peter Glaser Lecture: Space and a Sustainable 21st Century Energy System (2006)
RD 2.5	Solar Power from Space: European Strategy in the Light of Sustainable Development (2004)
RD 2.6	Environmental Impact of High-Power Density Microwave Beams on Different Atmospheric Layers (2004)
RD 2.7	Spark user manual
RD 2.8	Earth & Space Based Power Generation Systems: A Comparison Study (2005)
RD 3	ESA Work on Solar Power from Space: Concluding and Ongoing Activities (2008)
RD 4	IAA Decadal Assessment of Space Solar Power: A Progress Report (2021)
RD 5	A Path Forward for Space Solar Power: SPS-ALPHA Demonstrations to Operations (2017)
RD 6	SPS-ALPHA Mark-III and an Achievable Roadmap to Space Solar Power (2021)
RD 7	CASSIOPeiA – A new paradigm for space solar power (2019)
RD 8	Space Based Solar Power: De-risking the Pathway to Net Zero (2021)
RD 9	Space Based Solar Power as an Opportunity for Strategic Security (2007)
RD 10	Net Zero by 2050: A Roadmap for the Global Energy Sector (2021)
RD 11	A clean planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy, European commission (2018)
RD 12	Towards net-zero emissions in the EU energy system by 2050 (2020)
RD 13	Roadmap 2050: A Practical Guide to a Prosperous, Low-Carbon Europe (2010)
RD 14	From Baseload to Peak: Renewables Provide a Reliable Solution (2015)
RD 15	Quantifying a realistic, worldwide wind and solar electricity supply (2015)
RD 16	Measuring Progress Towards Climate Neutrality (2021)
RD 17	EIA projects nearly 50% energy use by 2050 (2019)
RD 18	Guide to Cost-Benefit Analysis of Investment Projects, European Commission (2014)

RD 19	MB4SE User Needs (2021)
RD 20	The New Economics of Innovation and transition: Evaluating Opportunities and Risk
AD 1	Microwave and Millimetre Wave Power Beaming (2021)
AD 2	Caltech Space Solar Power Initiative (SSPI) Results & Path Forward (2019)
AD 3	A Public / Private Program to Develop Space Solar Power (2020)
AD 4	21st Century Trends in Space-Based Solar Power Generation and Storage (2018)
AD 5	BEIS Net Zero Strategy (2021)
AD 6	Italy's Turning Point Accelerating new growth on the path to net zero (2021)
AD 7	EC (2011) European Energy Roadmap 2050
AD 8	EC (2013) EU energy, transport and GHG emissions trends to 2050
AD 9	EC (2021) Fit for 55 – delivering the 2030 climate target
AD 10	French Ministry of Ecological Transition (2020) summary of low carbon national strategy
AD 11	IEA (2016) Italy 2016 Energy Policy Review
AD 12	IEA (2016) Poland 2016 Energy Policy Review
AD 13	IEA (2019) United Kingdom 2019 Energy Policy Review
AD 14	IEA (2020) Germany 2020 Energy Policy Review
AD 15	IEA (2021) France 2021 Energy Policy Review
AD 16	IEA (2021) Spain 2021 Energy Policy Review
AD 17	IEA (2021) World Energy Outlook 2021
AD 18	KPMG (2021) Net Zero Readiness Index 2021
AD 19	McKinsey (2010) Transformation of Europe's power system by 2050
AD 20	McKinsey (2021) Net Zero Germany
AD 21	World Energy Council World Energy Scenarios Futures to 2050 Exec Summary (2013)
AD 22	The Impact of Biofuels on Food Security (2019)
AD 23	European Commission, A Clean Planet for All (2018)
AD 24	A Fresh Look at Space Solar Power: New Architectures, Concepts and Technologies (1997)
AD 25	Office for Energy and Renewable Energy 'Solar and Resilience Basics'
AD 26	What is the Role of Nuclear Power in the Energy Mix and in Reducing Greenhouse Gas Emissions? (2018)
AD 27	Roadmap 2050: A practical guide to a prosperous, low carbon Europe. Vol 1: Technical and Economic Assessment (2010)

AD 28	Technological Transfers from the European Space Programs: A Dynamic View and Comparison with Other R&D Projects. (2002)
AD 29	Net Zero by 2050: A Roadmap for the Global Energy Sector. (2021)
AD 30	A Technical Case Study On R&D And Technology Spillovers Of Clean Energy Technologies: Technical Study On The Macroeconomics Of Climate And Energy Policies. (2017)
AD 31	Climate Change and Energy, Overview (2004)

A.5 A Discussion on Cost-Benefit Analysis Methodology Assumptions, Caveats and Limitations

Assumptions

The cost benefit analysis undertaken in this study is subject to significant uncertainties owing to the long timeframe of analysis and the relative technical immaturity of the SBSP concept. To manage this, the cost benefit analysis proceeded with the following assumptions in mind:

Counterfactual scenario: In an evaluation of an infrastructure concept, only costs incurred and benefits in addition to those that would have occurred in the absence of investment in the concept should be included in the analysis. To identify this additionality, an alternative scenario that assumes no investment in the development of an SBSP concept for Europe has been undertaken. This is known as the counterfactual scenario. Owing to the significant technical barriers, uncertainties, and long development timeframe of the SBSP concept, we assume that development of a European SBSP concept is only achieved through a single pathway – i.e. we assume that a European SBSP will not be developed without public sector intervention. The Net Zero by 2050 scenario is informed by assumptions around policy developments at governmental – national and European Commission – levels. “A clean planet for all” sets out the European Commission’s long-term vision for a climate-neutral economy by 2050. As the best guide to future energy sector and emission developments, consideration is also taken of the most up-to-date pledges and published strategies both by national governments and the European Commission, such as the UK’s Net Zero Strategy and the European Commission’s “Fit for 55”. , An alternative ‘Business as Usual’ scenario that accounts for the impact of existing energy policies is also modelled. Following the Russian invasion of Ukraine, the situation is currently fluid, making projections to 2050 very difficult, but where possible the heightened energy security situation is considered. The two scenarios can be thought of as two differing levels of ambition and “green” policy intensification. By considering the two scenarios, it is possible to capture some of the (substantial) uncertainty inherent in the future developments of Europe’s energy mix. The ‘additionality’ or difference that SBSP makes to Europe is assessed relative to these counterfactual scenarios. More detail on this counterfactual scenario can be found in Chapter4 of TN [4].

Change: Proposed design, development, procurement, and operation of the European SBSP capability, measured in terms of quantitative benefits and costs that are additional to the counterfactual scenario. There are several SBSP concepts worldwide, but not all offer the capability to deliver baseload continuous power. CASSIOPeiA is one of the three most developed concepts, and its architecture is assumed as the reference design for this study, as detailed in ‘TN3 – System breakdown, costs, and technical feasibility’ document that precedes this report. This architecture is comprised of a space segment with a satellite and ground control infrastructure to collect, convert, and transmit solar energy from the sun to the SBSP infrastructure on the ground, and an energy segment with a network of rectennas and power stations that receive and convert solar energy into electricity for distribution to the wider electricity grid network. Additional satellites can be added to the concept and be costed in a scalable way. Economies of scale are assumed if multiple spacecraft are built and operated, resulting in a reduced marginal cost. Variations on this system, such as the addition of other satellites for increased energy supply capacity are assessed, with more significant variations on this architecture considered at a high-level. The basic assumption is that differences in the SBSP specification will alter both the cost of the system and, on the benefits side, the amount of energy supplied (and avoided carbon etc) that can be addressed by the SBSP system and therefore the benefit and costs that can be achieved.

Time period: The analysis will require several time periods to cover the development phase, construction and operation phases, each informed by the ‘TN3 – System breakdown, costs, and technical feasibility’ document. For the development phase a starting date of 2022 through to 2040 is assumed. This is suggested because the previous study (UK BEIS) noted a ~20-year development programme (including 2020), of which it allowed for a 2-year construction schedule per satellite. This assumption implies Full Operational Capability (FOC) of the system by 2040. This assumption is informed by a thorough technical assessment of the maturity of SBSP's enabling technologies, ensures that SBSP can make a meaningful contribution to 2050 targets, and enables comparison with alternative energy generation technologies. A first-generation service lifetime (and therefore the period over which benefits are to be estimated) is estimated to be 30 years (FOC to 2070).

Geography: Once operational, it is assumed that the European SBSP capability will be able to transmit energy across Europe. This assumes that the space segment of the system will exist at a fixed point in GEO with full coverage of Europe and that the ground segment, including rectennas for receiving transmitted energy, will be constrained to Europe. For the avoidance of doubt, 'Europe' is defined by the 'seven continent' definition of Europe, comprising an area of 10.18 million km2 or 2% of the Earth's surface, and 50 sovereign states. Coverage is assumed on the European landmass only. Europe-wide analysis for the cost-benefit analysis will, however, focus on the 30 countries that are either ESA Member States or EU Member States (or both), with Net Zero case studies highlighting the benefits and drawbacks of SBSP for the five countries that are forecast to consume the most energy over the period of analysis (France, Germany, Italy, Poland, United Kingdom).

Technical feasibility: This analysis estimates the benefits and costs of a European SBSP capability based on the technical specification and other performance parameters provided in the 'TN3 – System breakdown, costs, and technical feasibility' document. Considerations of technical feasibility and any limitations that are imposed is the product of this earlier phase of the study.

Stakeholder groups that are considered for this analysis include:

- Cost-bearers (Procurers of the SBSP capability, operators of the SBSP capability and electricity system operators)
- Beneficiaries (European energy users, European states, and European industry and citizens more broadly as users and economic/strategic/environmental beneficiaries of the European SBSP capability)

Benefits: Benefits are analysed against the counterfactual, or reference, scenario, i.e., the scenario that would occur in the absence of the construction of SBSP satellites and associated ground infrastructure. Benefits to energy users and to society at large (government, industry, citizens) are assessed over the time period of analysis, including those covering strategic, economic, environmental, and societal aspects. Benefits are monetized whenever possible, but some of the benefits are assessed qualitative terms as the type of benefit goes beyond a simple monetary value.

For example, economic benefits of SBSP include benefits to users (in the form of a potentially lower cost energy source, where the LCOE of SBSP vs alternatives is lower), and to society at large as a result of the spillovers associated with SBSP innovations enabling new terrestrial capabilities and earlier achievement of Net Zero, valued at the social cost of carbon that is avoided as a result of the introduction of SBSP relative to the counterfactual. Wider benefits from the resilience and security of energy supply, creation of manufacturing capability and high value employment in the form of spillovers, technology export, expanded space and reusable launcher capability are also explored, although harder to monetise.

Costs: The additional cost impacts of the European SBSP capability (relative to the counterfactual) is estimated as part of the technical contribution to this study (TN3) and is used as an input into this costs and benefits analysis. Further details of cost categories, parameters, and related data sources are provided in section 3.5 of TN4 [4], and cover all development, procurement, operation, and decommissioning costs over the time period of analysis.

In the first instance, cost parameters are based on the average cost associated with a 'first of a kind' system and learning rates and economies of scale adjustments are applied to generate costs for an 'nth of a kind system' from that point. For the space segment, 'first of a kind' costs are more expensive than those associated with subsequent 'nth of a kind' systems as economies of scale and learning efficiencies would reduce the cost of further manufacture of the system. However, these costs may be more expensive for the ground segment where, for example, less suitable land (i.e. more expensive / less optimal so implying additional conversion costs) may be available after provision for the first of a kind system. Nth-of-a-kind cost estimates will generate a more accurate picture of the costs of the system that Europe will likely provision for itself where n represents the expected scale of the system, so these costs are ideal for the cost-benefit analysis. The magnitude of costs for the SBSP system is accounted for in this analysis, but potential sources for this funding requirements and analysis of the role of the private sector are considered in TN4 which covers the development programme and commercial options for SBSP.

Discount rates:

- **Social Discount Rate:** Cost and revenue estimates over the time period of analysis are discounted to present value terms to allow a fair comparison of SBSP with alternative uses of public money. Specifically, the 3.0% Social Discount Rate (SDR) suggested by the European Commission for Member States is used . The analysis also considers different discount rates as sensitivities.
- **Discount rate for LCOE calculation:** a discount rate to account for the costs of capital and risks in the project is based on the projected hurdle rate required by institutional investors. The European space based solar power programme is a project with high uncertainty due to the long time horizon, dependency on technologies that are yet to be developed (in-orbit assembly, high efficiency solar PV panels, advances in wireless power transmission), and absence of any comparable projects that represent a precedent. On this basis, the hurdle rate used for SBSP's LCOE calculation should be a risk-adjusted rate as investors would need to be compensated for the additional project risk that they will be taking on. Conventional energy sources that rely on mature technologies and a long history of successful implementation have a risk-adjusted hurdle rate of 5-10%. The evidence base suggests that a higher degree of risk and uncertainty of the SBSP concept should be reflected through a higher hurdle rate. Projects of similar uncertainty, such as the pre-clinical stage of a biotech firm, moon mining, high-risk tech start-ups, or a commercially owned space station in Low Earth Orbit have been discounted with rates between 17-25%. Thus, a risk-adjusted discount range of 20% for SBSP has been chosen. Given the significance of this assumption and the possibility of future technical demonstrations which may reduce the perceived technical risk of the program, a number of different sensitivities are included in this analysis. A more detailed analysis and justification of the discount rate is provided in Section 6.4 of TN4 [4].

Further details of the assumptions used in the cost-benefit model can be found in Section 7.2 of TN4 [4].

A.6 Technology Readiness Level Definitions

TRL	ISO standard 16290:2013 Definition	Explanation
1	Basic principles observed and reported	Scientific research begins to be translated into research and development.
2	Technology concept and/or application formulated	Practical applications can be invented and research and development started. Applications are speculative and may be unproven.
3	Analytical and experimental critical function and/or characteristic proof-of-concept	Active research and development is initiated, including analytical / laboratory studies to validate predictions regarding the technology.
4	Component and/or breadboard functional verification in laboratory environment	Basic technological components are integrated to establish that they will work together in a laboratory environment, which is highly controlled. Bench scale.
5	Component and/or breadboard critical function verification in relevant environment	The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment, more like the target environment. Pilot scale (power/dimension).
6	Model (physical prototype) demonstrating the critical functions of the element in a relevant environment	A representative model or prototype system is tested in a relevant environment. This is either exposed to the analogous environmental conditions on Earth for ground systems, or in space for satellite systems with conditions analogous to GEO. e.g. for satellite technologies, they have been operated in space, either in isolation or part of another system. Pilot scale (power/dimension).
7	Model (physical prototype) demonstrating the element performance for the operational environment	System prototype demonstration in a space environment. A prototype system that is near, or at, the planned operational system. At or near full scale.
8	Actual system completed and accepted for flight ("flight qualified")	In an actual system, the technology has been proven to work in its final form and under expected conditions, through test and demonstration (ground or space). Full Scale.
9	Actual system "flight proven" through successful mission operations	The system incorporating the new technology in its final form has been used under actual mission conditions. Full scale.

A.7 Development Degrees of Difficulty

Development Degree of Difficulty	Definition
Very Low	There are no unknowns that require further work to allow this technology to be deployed. Increasing the scale of deployment is not considered a challenge.
Low	There are few unknowns that require further work to allow this technology to be deployed at scale, and there is a straightforward approach to addressing them. Increasing the scale of deployment is not considered significantly challenging.
Medium	Some further work is required to allow this technology and, although the approach is not clearly defined, it appears to be similar to other technological developments. Increasing the scale of deployment is considered somewhat challenging but has been achieved for analogous technologies.
High	There are significant unknowns present. It will take some work and iteration in order to develop an approach to mature the technology. Increasing the scale of deployment is considered challenging and beyond what has been achieved for analogous technologies.
Very High	There are significant unknowns present and a high likelihood of unknown-unknowns that are yet to emerge. It will take significant work and iteration in order to develop an approach to mature the technology. Increasing the scale of deployment is considered extremely challenging and well beyond what has been achieved across human endeavours.

A.8 Sub-System Development Path - Philosophy

Core Power Systems

<table>
<tr><th>Satellite</th><th colspan="2">Satellite Collect</th></tr>
<tr><td rowspan="4">Activities</td><td rowspan="4">The development of the mirror system will start in Development Phase 1. While the full mirror system is not tested until Development Phase 3 the configuration of the mirror system will need to be developed in parallel with the core modules as it will have an impact on the convert, structure and thermal management subsystems.</td><td>Timeline</td></tr>
<tr><td>Start: Year 4

Duration: 15 years</td></tr>
<tr><td>Constraints / Issues</td></tr>
<tr><td>Defining the level optical clarity needed on the mirror surface.

The optical acceptance angle of the photovoltaic system</td></tr>
<tr><td>Dependencies</td><td colspan="2">The choice of photovoltaic technology used for Satellite Convert

Configuration of the satellite modules</td></tr>
</table>

<table>
<tr><th>Satellite</th><th colspan="2">Satellite Convert</th></tr>
<tr><td rowspan="4">Activities</td><td rowspan="4">Development of the photovoltaics will start at the beginning of Development Phase 1. CASSIOPeiA is designed to use high concentration photovoltaics, the initial development activities centre around the choice of photovoltaic technology. Ground testing in Development Phase 1 will confirm the arrangement of primary and secondary optics and inform the development of core modules. The performance of the photovoltaic system in the varying space environments will be monitored through Development Phases 2 and 3 and the data collected will be used in the development of the system.</td><td>Timeline</td></tr>
<tr><td>Start: Year 1

Duration: 14 years</td></tr>
<tr><td>Constraints / Issues</td></tr>
<tr><td>Choice of PV technology to optimise efficiency and longevity at an economic unit cost.</td></tr>
<tr><td>Dependencies</td><td colspan="2">Configuration of the satellite modules</td></tr>
</table>

<table>
<tr><th>Satellite</th><th colspan="2">Satellite Transmit</th></tr>
<tr><td rowspan="3">Activities</td><td rowspan="3">The wireless power transmission elements of CASSIOPeiA are the most novel aspects of the satellite. Development will start at the beginning of Development Phase 1 with a series of ground-based trials. It is envisaged that these trials will be carried out from a balloon or high-altitude platform system, allowing the beaming distance to be increased in successive trials and the effects of the</td><td>Timeline</td></tr>
<tr><td>Start: Year 1

Duration: 18 years</td></tr>
<tr><td>Constraints / Issues</td></tr>
</table>

	upper atmosphere on the power beam transmission performance to be investigated. By the end of Development Phase 1, the basic configuration of the wireless power transmission elements of the core modules will have been established. These will be tested at an increasingly larger scale as the size of the demonstration satellite increases through Development Phases 2 and 3, providing the opportunity to streamline their performance and improve overall system efficiency.	End to end efficiency and minimising side-lobes. Controlling interference to other assets. Public attitudes to WPT.
Dependencies	Configuration of the satellite modules Allocation of frequency bands for WPT. Regulation on safe microwave power limits.	

Satellite	Satellite Structure	
Activities	The structural design is the least mature element of the satellite concept. Development of the structural solution for the satellite needs to start in Development Phase 1. The initial investigations will focus on developing the requirements, recognising that any structure of this scale has yet to be put into orbit. By the end of Development Phase 1, a design concept that satisfies the requirements will be needed. The structure of the demonstration satellite used in Development Phase 2 will employ elements of the overall structural design. However, ground-based testing during Development Phase 2 will be used to explore the complete structural design solution and provide a basis for the structural design of the demonstration satellite launched in Development Stage 3.	**Timeline** **Start:** Year 2 **Duration:** 17 years **Constraints / Issues** Understanding how the structural dynamics affects system performance. Availability of suitable microwave transparent materials.
Dependencies	Architectural design of the satellite	

Satellite	Satellite Thermal Management	
Activities	The concept employs passive radiative cooling and sets the resultant temperature of the PV cells as a design constraint on the modules. Development of the radiative cooling solution will start in Development Phase 1 as a key element of the functional performance of the core modules. The trials on the demonstration satellites in the subsequent phases will provide an opportunity to test the cooling performance and provide information to inform ongoing development and optimisation of the solution.	**Timeline** **Start:** Year 3 **Duration:** 12 years **Constraints / Issues** Availability of suitable terrestrial test facilities
Dependencies	Configuration of Convert & Transmit sub-systems and choice of PV technology	

<table>
<tr><th>Satellite</th><th colspan="2">Satellite Control System</th></tr>
<tr><td rowspan="4">Activities</td><td rowspan="4">The key developments for the satellite control system involve providing distributed communications between the modules in the core of the satellite and a phase reference to control the microwave beam. Development of this sub-system needs to start in Development Phase 2, with the initial solutions being available for the Phase 2 demonstration satellite and the full functionality tested on the Development Phase 3 demonstration satellite.</td><td>Timeline</td></tr>
<tr><td>Start: Year 7
Duration: 12 years</td></tr>
<tr><td>Constraints / Issues</td></tr>
<tr><td>The physical size of the satellite and hence the communication distances.</td></tr>
<tr><td>Dependencies</td><td colspan="2">Establishing the basic performance parameters of the transmit sub-system.</td></tr>
</table>

<table>
<tr><th>Satellite</th><th colspan="2">Satellite Station Keeping</th></tr>
<tr><td rowspan="4">Activities</td><td rowspan="4">The initial designs of the satellite will use electric thrusters to provide the station keeping. The key development challenge is understanding the dynamics of such a large structure and therefore the requirements for the thrusters. The development will start with analytical studies during Development Phase 2 to define the requirements for the system to be integrated into the demonstration satellite in Development Phase 3. The trials on the satellite in Development Phase 3 will be used to confirm the requirements and identify further optimisation of the subsystem for the preproduction prototype in Development Phase 4.</td><td>Timeline</td></tr>
<tr><td>Start: Year 8
Duration: 11 years</td></tr>
<tr><td>Constraints / Issues</td></tr>
<tr><td>Maximising the operational life of the satellite at minimum cost</td></tr>
<tr><td>Dependencies</td><td colspan="2">Architectural design of the satellite
Choice of operational orbit for the satellites</td></tr>
</table>

<table>
<tr><th>Satellite</th><th colspan="2">Satellite Communications</th></tr>
<tr><td rowspan="4">Activities</td><td rowspan="4">The satellite communications systems will use conventional communication technology. The development challenges involve integration of this technology into the modules of the satellite core and providing suitable encryption to ensure secure operations. The engineering of the system will start in Development Phase 2 with trials of the initial solutions on the first demonstration satellite. The capability of the system will be developed over Development Phases 3 so that the system is fully mature for use on the pre-production prototype in Development Phase 4.</td><td>Timeline</td></tr>
<tr><td>Start: Year 7
Duration: 8 years</td></tr>
<tr><td>Constraints / Issues</td></tr>
<tr><td>Deployment of encryption keys</td></tr>
<tr><td>Dependencies</td><td colspan="2">Integration with existing satellite operations centres</td></tr>
</table>

<table>
<tr><th>Ground Stations</th><th colspan="2">Ground Receive & Convert</th></tr>
<tr><td rowspan="4">Activities</td><td rowspan="4">An operational rectenna will be required in development phase 3, to receive the microwaves transmitted from the demonstration satellite. The basic arrangement of a rectenna was established in the late 1970's by Raytheon and NASA. The key developments that will be required centre around optimising the configuration to maximise efficiency and energy collection while minimising cost. The engineering development of the rectenna can start in Development Phase 1 with early stage trials in Development Phase 2.</td><td>Timeline</td></tr>
<tr><td>Start: Year 3
Duration: 12 years</td></tr>
<tr><td>Constraints / Issues</td></tr>
<tr><td>Configuration of the antenna grid to maximise power collection.
Public acceptance of WPT</td></tr>
<tr><td>Dependencies</td><td colspan="2">Architectural design of the satellite
Allocation of frequency bands for WPT.
Regulation on safe microwave power limits.</td></tr>
</table>

Ground Stations	Ground Distribution & Grid Connection	
Activities	Ground distribution and grid connection will use the same technologies as employed in terrestrial solar farms. Therefore, specific development of these systems is not required. These systems will be integrated into the ground station design as required.	**Timeline** **Start:** Year 9 **Duration:** 6 years **Constraints / Issues** Adaptability of existing technology
Dependencies	Rectenna architecture established Availability of a suitable site with grid access	

Ground Stations	Ground Structure	
Activities	The ground structure supports the rectenna, therefore it will be required in Development Phase 3. The support structure will be similar to wind turbine columns or telegraph poles, therefore no specific developments are required. The engineering of a cost optimised support structure can start during Development Phase 2	**Timeline** **Start:** Year 8 **Duration:** 7 years **Constraints / Issues** Cost optimisation
Dependencies	Rectenna architecture established Availability of a suitable site	

Ground Stations	Ground Operations: Power Control Interface	
Activities	The power control interface will use similar elements to other grid connected power generation systems, therefore there are no specific development activities. The engineering of the system can be carried out in Development Phase 3.	**Timeline** **Start:** Year 12 **Duration:** 5 years **Constraints / Issues** Adaptability of existing technology
Dependencies	Establishing the operational parameters for the ground system and the grid connections Commercial agreements with grid operators	

Ground Stations	Satellite operation: Mission Control Interface	
Activities		**Timeline**

	The mission control interface will use similar elements to existing satellite communications systems, therefore there are no specific development activities. It is anticipated that the development missions will use existing facilities. The owners of operational systems may choose to build their own mission control centres.	**Start:** Year 7 **Duration:** 8 years **Constraints / Issues** Adaptability of existing technology
Dependencies	Commercial agreements with mission control centres	

Ground Stations	Ground Communications	
Activities	The encrypted retrodirective pilot beam that forms part of the ground communications system requires some development. This will be developed in parallel with the wireless power transmission elements of the satellite, starting with the ground-based trials in Development Phase 1 and continuing to grow in capability as the power beaming distance is increased through Development Phases 2, 3 & 4.	**Timeline** **Start:** Year 3 **Duration:** 12 years **Constraints / Issues** Deployment of encryption keys
Dependencies	Integration with Satellite Communications sub-system	

Enabling Systems

Satellite	Spacelift	
Activities	Spacelift is used as a generic term to cover the delivery of the satellite hardware to its final orbit. Assuming the solar power satellite is in geostationary orbit there will be two key elements of spacelift: contracting a commercial launch provider to deliver packages to a suitable transfer orbit, and a bespoke orbit transfer vehicle to take the packages from the transfer orbit to geostationary orbit. The orbit transfer vehicle will be needed in Development Phase 4 to deliver the pre-production prototype into geostationary orbit. The engineering development of the orbit transfer vehicle can start in Development Phase 1 and continue through the following Phases with ground tests and initial qualification completed before Development Phase 4. While the delivery of modules to transfer orbit will be bought as a service and therefore not developed as part of this programme, the design authority for the programme will need to send a clear demand signal to industry in terms of the scale, timing, and profile of the space lift requirement, as well as commitment to the space lift service procurement. Current 'super-heavy' space lift capacity to deliver the system in orbit is limited so a large expansion in available capacity is needed	**Timeline** **Start:** Year 1 **Duration:** 14 years **Constraints / Issues** The shape and dimensions of the payload bay in candidate launch system. The launch environment imposed on the payload. The launch tempo that can be sustained

	to deliver the first of a kind system and subsequent systems that are needed to address the available demand for SBSP (as detailed in TN4). A clear demand signal to industry may encourage investment in space lift capacity, including expansion from existing providers (SpaceX and their Starship vehicle), known entrants (Blue Origin, Arianespace), and potential unknown entrants (e.g. new European providers). The requirements for such a vehicle will need to be outlined in the it will be necessary to identify candidate launch vehicles early in the development cycle of the solar power satellite, given the long lead times. The shape and dimensions of the payload bay and the launch environment will be key considerations in the specification of the satellite modules and their assembly sequence. This information will be needed at the start of Engineering Phase B of the Satellite.	
Dependencies	Availability of a commercial launch providers with sufficient capacity to deliver the payloads to orbit.	

Satellite	Satellite component/module manufacture	
Activities	The economics of the systems depends on driving down the costs of the satellite modules. The hyper-modular architecture of the satellite lends itself to volume manufacture, utilising the techniques employed in consumer electronics and the automotive industries. The components for the Development Phases 1 and 2 can be sourced from existing commercial sources and the modules assembled under contract manufacture. By Development Phase 3 it is likely that bespoke components will need to be sourced from the supply chain and while module assembly could be supplied by contract manufacture it will become increasingly attractive to grow an indigenous module manufacturing capability.	**Timeline** **Start:** Year 4 **Duration:** 9 years **Constraints / Issues** Cost optimisation of the satellite modules, design for manufacture. Material availability.
Dependencies	A supply chain that responds to the demand presented by the volume of components required.	

Satellite	In-orbit assembly & maintenance	
Activities	It is envisioned that the in-orbit assembly of the satellite will be carried out by small termite inspired robots that travel across the satellite modules. These robots will be needed to assemble the demonstrator in Development Phase 3. The engineering development of the assembly robots can start with Feasibility in Development Phase 1 and continue through	**Timeline** **Start:** Year 6 **Duration:** 9 years **Constraints / Issues**

	the following Phases with ground tests taking place during Development Phase 2 and qualification at the start of Development Phase 3. Maintenance of operational satellites will involve replacement of failed modules, thus utilising the same robots.	Establishing the build sequence of the satellite Establishing the logistics supply chain for delivery of modules to the robots Availability of suitable terrestrial test facilities
Dependencies	Rectenna architecture established Module characteristics confirmed	

Satellite	Decommission satellite	
Activities	The strategy for decommissioning operational satellites will be a key constraint on the architectural design of the satellite. Decommissioning will need to be considered in Engineering Phase A of the satellite to ensure that there are a range of possible options available for the operational system. An outline scheme for decommissioning the demonstration satellites produced in Development Phases 2, 3 & 4 has been discussed in TN3.	**Timeline** **Start:** Year 3 **Duration:** 12 years **Constraints / Issues** The physical size of the satellite
Dependencies	Agreement from relevant authorities	

Ground Stations	Rectenna Manufacture	
Activities	While the rectenna does not present the same level of hyper-modularisation as the satellite it does have a degree of modularisation. While the rectenna does not present the same level of hyper-modularisation as the satellite, it does have a certain degree of modularisation. Therefore, it will benefit from a similar approach to establishing an indigenous manufacturing capability as the satellite.	**Timeline** **Start:** Year 11 **Duration:** 8 years **Constraints / Issues** Cost optimisation of the rectenna modules, design for manufacture. Material availability
Dependencies	A supply chain that responds to the demand presented by the volume of components required.	

Ground Stations	Power Station and Operation Station Construction	
Activities	Construction of both the power station and operation station are conventional construction projects. Hence no specific development activities will be needed. An initial capability for both these stations will be needed for the demonstration in Development Phase 3, with an extended capability in Development Phase 4.	**Timeline** **Start:** Year 11 **Duration:** 8 years **Constraints / Issues** Nil
Dependencies	Availability of a suitable site Engaging a design and build contractor	

Ground Stations	Maintenance of Ground Stations	
Activities	Maintenance of the ground stations does not involve any bespoke operations. Therefore, there are no specific development activities.	**Timeline** **Start:** Year 11 **Duration:** 8 years **Constraints / Issues** Nil
Dependencies	Engaging a maintenance contractor	

Ground Stations	Decommission Ground Stations	
Activities	Decommissioning of the ground stations does not involve any bespoke operations. Therefore, there are no specific development activities. Decommissioning won't be required until the end of life of the system, so the activities at this stage are limited to planning for decommissioning.	**Timeline** **Start:** Year 8 **Duration:** 11 years **Constraints / Issues** Decommissioning to be a requirement in the design specification of the ground stations.
Dependencies	Engaging a design and build contractor	

A.9 Current launch service capacity constraints

The supply of launch services to deliver SBSP into geostationary transfer orbit (GTO) will be a major constraint to the supply of fully operational SBSP systems in orbit.

This issue can be understood by considering the total launch requirement of a single 1.44 GW SBSP system under a conservative assumption of availability of heavy-lift launch service:

- The total spacelift mass that is needed to put a 1.44 GW SBSP system into orbit is 2,491 metric tons. This is equal to the satellite mass of 1,816 metric tons plus the mass of station keeping propellant, assembly robots, and OTV[9].
- Starship, a planned fully reusable super heavy-lift launch vehicle that is being developed by SpaceX, represents the only near-term launch concept which can deliver SBSP's modular structures to GTO at a reasonable cost and in the right orbit. This system can deliver a total mass of between 21-29 T to GTO[10], assuming that Starship is refuelled in orbit using propellent that is also delivered to GTO.

Taken together, these two assumptions suggest that between 86 and 119 Starship launches are required to deliver a single 1.44 GW SBSP system into orbit.

To date, Starship has obtained approval to operate from two of the USA's three spaceports for heavy lift launch operations that are accessible to SpaceX (Kennedy Space Centre in Florida, and Boca Chia in Texas)[11]. Current environmental limits restrict Starship to a total of just 30 launches per year from these sites (a maximum frequency of 25 launches from KSC[12], and a proposal for five launches at BC[13]). About 25% of this capacity is likely to be dedicated to SpaceX's strategic priority – the launch and replenishment of the Starlink LEO constellation. This suggests a maximum of 22 Starship launches per year for SBSP, assuming no competition from other customers for Starship's remaining launch capacity. This would suggest that a single SBSP system would require between 4 and 6 years for full deployment based on currently planned super-heavy launch capacity.

However, given the scale of demand for launch mass that an SBSP programme would represent, it is likely that the supply of super-heavy launch services internationally will respond to this need. For example, the current launch capacity for Starship could conceivably increase and Europe could develop a fully sovereign super-heavy lift launch capability:

- Starship launch capacity (and/or other non-European alternatives) could increase from a combination of increased launch frequency from each site and an increase in the number of launch sites. An increase in the number of sites from two to four and a relaxation in environmental limits for each site to a maximum of 96 launches per year (i.e. a four-fold increase in the KSC limit) would increase Starship (or equivalent) launch capacity 16-fold from 24 to 384 Starship launches per year.
  - Given Starship's intended use for interplanetary exploration, human spaceflight, cislunar activities, existing GEO/LEO launch requirements, and other activities, the majority of this capacity (75%) can be assumed to support non-SBSP activities. The remaining 25% of this capacity can be assumed to service SBSP requirements. This gives us a total of 96 Starship launches per year for SBSP.

[9] Please see 'TN3 – System breakdown, costs, and technical feasibility'
[10] SpaceX's Starship User Guide indicates that a single launch can deliver 21 T to GTO. Source: https://www.spacex.com/media/starship_users_guide_v1.pdf. Frazer Nash estimate that Starship can deliver up to 29 T to orbit with each launch. This assumes that Starship is refuelled in orbit to deliver more efficient lift capability. These calculations are based on 2 Starship launches (one carrying payload the other fuel) delivering 57.9T of satellite plus the fuel needed for the OTV to get to GEO. A single Starship therefore delivers 59/2 T, or 29 T.
[11] The three sites are: Cape Canaveral (Florida, US Space Force), Kennedy Space Center (Florida, NASA), Boca Chia (Texas, SpaceX). Launch Site One West Texas (Texas, Blur Origin) will also support heavy lift operations, but for the private exclusive use of Blue Origin. Please see here for details: https://www.faa.gov/space/spaceports_by_state
[12] Please see: https://netspublic.grc.nasa.gov/main/20190919_Final_EA_SpaceX_Starship.pdf
[13] Please see: https://www.faa.gov/sites/faa.gov/files/2022-06/Final_PEA_Executive_Summary.pdf

- Any European sovereign super-heavy launch vehicle with comparable launch capacity to Starship will likely only be able to launch from Europe's only suitable site in Kourou, Guinea because of the need for an equatorial launch site away from population centres. Europe does not have access to any other launch sites with characteristics that can accommodate this type of launch.
  - Assuming similar environmental restrictions as Starship and a similar relaxation of these restrictions, we get a maximum of 96 launches per year.
  - As with Starship, some of this launch capacity will be needed for other things, but most of this (~80%) can be assumed to support SBSP. This gives us a total of 77 European launches per year for SBSP.

Given the spacelift requirements for SBSP, these two assumed developments suggest that a total of 173 launches per year could be available to deliver SBSP to orbit. This suggests that a maximum of between 1.5 and 2 SBSP systems can be delivered into orbit per year based on the above assumptions.

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