Space Based Solar Power as a Contributor to Net Zero

Phase 1: Engineering Feasibility Report

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SYSTEMS AND ENGINEERING TECHNOLOGY

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Originating Office: FRAZER-NASH CONSULTANCY LIMITED
Stonebridge House, Dorking Business Park, Dorking, Surrey, RH4 1HJ
T: 01306 885050   F: 01306 886464   W: www.fnc.co.uk

EXECUTIVE SUMMARY

‘Net Zero’ is the goal and legal obligation for the UK to decarbonise the economy by 2050. BEIS has commissioned Frazer-Nash to study the engineering feasibility, cost and economics of Space Based Solar Power (SBSP), as a possible future energy technology which could make a contribution to Net Zero. This report presents the findings of Phase 1, an assessment of the engineering feasibility.

The study has been informed by published literature supported by structured stakeholder workshops with leading SBSP inventors as well as senior figures in UK industry and academia. The necessary technology and industrial capability has been considered in both a UK and wider international context.

The outputs include:

- A review of three candidate SBSP concepts.
- A comparison of SBSP with other low carbon generation technologies.
- A comparison of scenario for the future UK energy mix with and without SBSP.
- An assessment of the underpinning technology maturity and engineering barriers to realise SBSP.
- UK and international roadmaps for the development of a 10GW SBSP capability.

Findings:

- This study has found that the engineering challenges could be overcome so that the technology could be developed and deployed operationally within the 2050 timeframe.
- SBSP offers characteristics as an energy generation technology which could work as part of the future Net Zero energy system scenarios.
- The three SBSP concepts considered all offer a potential basis for a future system, though they are each quite different in architecture, and thus offer different advantages, costs and technical risks.
- The roadmap timescales require early technology development effort in high concentration solar photovoltaics, large lightweight structures for space, wireless power transfer, robotic orbital assembly and satellite decommissioning.
- A series of scaled technology demonstration steps has been identified to establish early confidence in, and understanding of, the system.
- The UK is well positioned across a range of technologies to play a leading role in future SBSP development
-

Recommendations:

- As SBSP appears feasible from an engineering perspective it is recommended that Phase 2 of this project is undertaken to better understand the cost and economic impact.
- If the outputs of Phase 2 are acceptable then there should be initial assessments across societal impact, social acceptance, international and local legal implications, standards development and environmental impact.
- A Front-End Engineering Design study is performed to develop initial system requirements, and develop and assess the architecture and design options, performance, risks and through-life costs to a greater degree of confidence.

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1. INTRODUCTION

1.1 BACKGROUND

1.1.1 This report

BEIS has commissioned Frazer-Nash to study the engineering feasibility, cost and economics of Space Based Solar Power, as a possible future energy technology which could make a contribution to Net Zero. This report presents the findings of Phase 1, a high level assessment of the engineering feasibility. Phase 2 will address the cost and economics.

1.1.2 Net Zero

'Net Zero' is the UK Government goal and legal obligation to decarbonise the UK's economy by 2050. The Committee on Climate Change has put forward a number of scenarios for the UK to achieve Net Zero, with alternative combinations of different low carbon energy technologies together with societal change. But there are many challenges to be overcome in delivering these scenarios, and all would require solutions which are currently speculative (Committee on Climate Change, 2019). Any new technology which might support the delivery of this vital target is worth considering.

1.1.3 Future Energy Technology priorities

BEIS has overarching priorities for any new renewable energy technology, which must:

- Deliver affordable Levelised Cost Of Energy (LCOE) both for homes and industry;
- Provide reliability, resilience, and security of supply for the UK;
- Support UK prosperity and high value jobs;
- Deliver a substantial contribution to Net Zero by 2050.

1.1.4 Space Based Solar Power

Space Based Solar Power (SBSP) is the concept of collecting solar energy in space and beaming it to Earth via wireless power transmission. One of the greatest advantages this provides compared to terrestrial renewables is that it has the potential to provide almost continuous base load renewable energy.

1.1.5 A Fresh Look

After periods of study from the 1970s onwards, and with the imperative to find new sources of clean energy, SBSP is being actively considered again by many nations (Jaffe, 2020). Factors such as the reducing cost of commercial space launch, the advancing maturity of enabling technologies, and improved modular Solar Power Satellite concepts are all making SBSP appear more attractive than in the past.

1.2 STUDY SCOPE

This work aims to provide an evidence base on the likelihood of the SBSP technology to become commercially feasible before 2050 from an engineering and economic perspective. This will allow the government to make decisions about whether to take forward further investigations and policy development. It will also allow the government to better understand areas of complementarity between energy policy, R&D policy and support for the growth of emerging sectors, new materials technologies and the space sector.

This report covers the review of the engineering feasibility of SBSP, which:

- Investigates available SBSP designs and costs
- Understands the engineering barriers in delivering SBSP
- Investigates a selection of a reference engineering designs and understands their likelihood and capabilities to contribute to UK Net Zero target
- Develops a technology roadmap to deliver the complementary technologies e.g. in orbit assembly, and the current state of play of these technologies
- Highlights the advantages and disadvantages of SBSP including environmental and land impact assessment.

It is recognised that political, legal, regulatory and environmental impacts are important factors that influence the viability of future adoption of SBSP however this work concentrates on the engineering feasibility; other factors will need further consideration. There are a wide range of applications and concepts of operation proposed for SBSP. To provide a clear focus for the work this report considers SBSP used to provide low intermittency power generation into the national grid. The study has drawn on published literature and information gathered from experts.

In order to conduct this high-level assessment of feasibility it has been necessary to develop assumptions to allow us to cover this broad subject within the scope of this work:

- An individual SBSP system will provide 2GW of electrical power to the grid.
- The satellite will be in an orbit which allows for continuous power transmission to the UK, with the exception of the 70 minute interruption at spring and autumn equinox, as well as shorter interruptions of a few days either side of each equinox.
- The energy will be transferred via microwave beaming to a rectenna (as opposed to laser transmission, or thermal plant on the surface).
- Lift mass is the critical constraint on launches rather than geometry and mass position within the space craft.
- Technology transfer from similar industries is available and the pace of innovation within those sectors, such as launch costs, continues.

To provide a focus for the investigations we have considered three of the leading SBSP concepts as reference designs:

- Constant Aperture Solid-State Integrated Orbital Phased Array (CASSIOPeiA)
- Solar Power Satellite via Arbitrarily Large Phased Array (SPS-ALPHA)
- Multi-rotary Solar Power Satellite (MR-SPS).

1.3 METHODOLOGY

To deliver the scope of the project we have gathered information from:

- Publically available literature from the UK, EU, US, China and Japan.
- Discussions with two international experts in Space Based Solar Power, and inventors of two of the concepts studied;
- Three workshops with technology leaders in the UK space industry, SBSP experts and academia to establish:

  - The Technology Readiness Levels (TRLs) of critical enabling technology
  - The major engineering barriers that need to be overcome to realise SBSP
  - A roadmap for the development of SBSP.

We have developed a system breakdown to consider the whole life cycle of an SBSP system, together with assessment criteria relevant to BEIS's interests. Using the information gathered, the system breakdown and the assessment criteria we have:

- Explored three SBSP concepts to understand their characteristics;
- Compared SBSP to other generation technologies;
- Compared future UK energy scenarios with and without SBSP;
- Reviewed SBSP from a grid integration engineering perspective.

This has allowed us to consider if SBSP can contribute to Net Zero and understand if the required engineering development is feasible to deliver an operational SBSP capability by 2050.

1.4 STRUCTURE OF THIS DOCUMENT

This document is structured as follows:

- **Section 2 - Space-Based Solar Power Architectures.** Defines the structure of the SBSP system of interest used in this study.
- **Section 3 - Space-Based Solar Power Designs.** Explains SBSP technical challenges and compares three potential designs.
- **Section 4 – System Engineering Feasibility Assessment.** Using the subsystems defined in Section 2 and the critical enabling technologies, each subsystem has been assessed for technology feasibility. Whole system considerations are also addressed.
- **Section 5 - SBSP As Part of the UK Energy Mix.** Discusses the application of SBSP in the UK and the strengths and weaknesses against other technology. Comparing Net Zero scenarios with and without SBSP to determine whether it is a genuine competitor to more established terrestrial energy sources.
- **Section 6 - Technology Roadmap.** A roadmap for the UK to develop a SBSP capability which able to provide a significant contribution to the UK energy mix by 2050. The feasibility of the roadmap is then discussed.
- **Section 7 – Summary and Recommendations.** Defines whether SBSP is technically feasible as a contributor to the UK's 2050 Net Zero target. Highlighting key engineering barriers that may prevent SBSP becoming a significant power source for the UK.

2. SPACE-BASED SOLAR POWER – WHOLE SYSTEM VIEW

2.1 OVERVIEW OF SBSP

A typical SBSP system concept comprises a massive, kilometre scale satellite in Geostationary Earth Orbit (GEO), about 36,000 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 about 3 hours where the satellite is in the Earth's shadow. This means that SBSP can provide almost continuous base load power all year round.

The satellite features large lightweight solar panels, often with a system of mirrors to reflect and concentrate sunlight onto the panels. The electricity generated by the solar panels is converted into microwave radiation and is beamed to a rectifying antenna (a 'rectenna') on the ground. The frequency of the microwave beam is chosen to minimise attenuation from the atmosphere, clouds or precipitation, and the maximum beam intensity is set to safe limits.

A secure pilot beam is transmitted from the ground to the satellite to allow the microwave beam to lock onto the correct target. The ground 'rectenna' converts the electromagnetic energy into direct current electricity which can be converted and transformed to provide power to the grid with acceptable characteristics.

A complete SBSP system could comprise a constellation of such satellites, providing a substantial amount of power as part of a nation's Critical National Infrastructure.

The solar power satellites considered in this report are of the order of kilometres in size, generate around 3.4GW of electricity on the satellite, transmit the microwave power at 2.45GHz with a maximum beam intensity of around 230 W/m^2 (one quarter of the intensity of midday sunlight) and produce around 2GW of electrical power to the grid.

2.2 WHOLE SYSTEM VIEW

We have developed the Whole System View in Figure 1, to provide an assessment basis for the study. This includes the SBSP satellite, ground facilities, power distribution and those enabling systems necessary to realise the capability, from development to decommissioning.

The SBSP System is decomposed into the Core System and the Enabling Systems through life. These are, in turn, decomposed into subsystems. The subsystems are allocated critical enabling technologies, which form a common structure throughout the study.

Throughout this study a number of comparisons are made of systems at varying levels.

- Whole SBSP systems comprise of all the subsystems contained within the "SBSP System Boundary" box with the green dashed line in Figure 1 and are compared. Alternative SBSP designs are compared to each other in Section 3.
- SBSP systems are compared to other generation systems by comparing their characteristics to that of alternative low carbon generation technologies, shown as the smallest black box with a dashed yellow line to the top right of Figure 1. This comparison is done in Section 5.
- UK generation scenarios in 2050 are compared by considering alternative versions of the "Electricity System" within the purple dashed line, again in the top right of Figure 1. This comparison is done in Section 5.

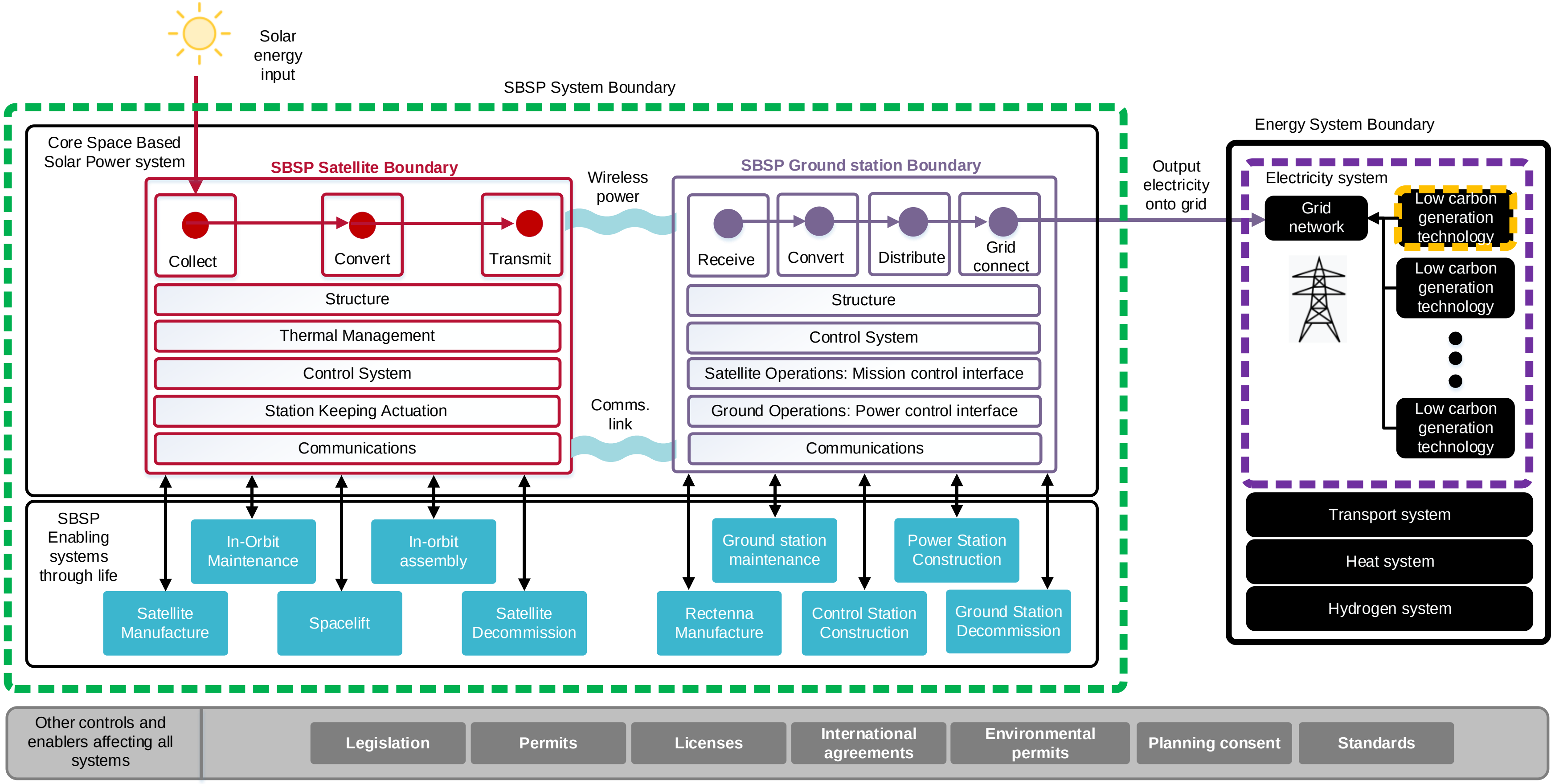

Figure 1: Whole System View for this study

3. SPACE-BASED SOLAR POWER DESIGNS

3.1 TECHNICAL CHALLENGES AND DESIGN ASSUMPTIONS

This section provides some introductory context for the description of the three leading concepts chosen as reference designs for this investigation. At this early stage of technical maturity not all aspects of technology development have been addressed or finalised therefore there are many assumptions made within the designs. The main technical challenges that have to be addressed by SBSP designs are summarised below. The following sections highlight the different and innovative ways in which the designers of three different concepts have addressed these challenges with their designs for GW scale baseload power generation.

3.1.1 Sun-Earth pointing

3.1.1.1 Maintaining the angle

A solar power satellite operating in GEO remains at the same point above the Earth throughout its orbit. Throughout the orbit the angle between the Sun-pointing solar collector and the ground-pointing microwave transmitter is constantly changing. Thus if the solar collector is always pointed towards the Sun, the microwave beam has to be steered to always point at the correct location on the Earth. Conversely if the microwave beam is fixed to point at the Earth the solar collector must be steered to always face the Sun. In this way the system can deliver near continuous power. Some concepts use mechanical steering while others use solid state electronic beam steering to address this challenge.

3.1.1.2 Pointing accuracy

For concepts using mirrors as part of the collector, these must hold alignment within typically 1 degree (Frazer-Nash Consultancy, 2020) to maintain the high sun concentration onto the PV elements. The mirrors must maintain reasonable uniformity to avoid creating local hotspots on the PV elements.

The microwave beam must be steered very precisely to within one thousandth of a degree if the rectenna is to capture at high percentage of the beam. All concepts assume a retro-directive pilot beam from the Earth to the satellite to maintain this pointing precision.

3.1.2 Architecture

3.1.2.1 Size and scaling

The size of the SBSP satellite is governed by the by the size of the microwave antenna, which depends on the laws of diffraction physics and the design beam intensity. There is a direct relationship between the size of the antenna on the satellite and the rectenna on the ground; increasing the size of the antenna reduces the size of the rectenna. There is an imperative to minimise the size (and hence the mass) of the satellite for economics, but there are also practical considerations for the size of the rectenna. For an SBSP satellite in GEO, and beaming at 2.45GHz, the transmitting antenna needs to be several kilometres in diameter. As the size of the antenna is reduced in size it rapidly reaches the point at which no useful power is received at the rectenna. This constraint dictates the size, location and configuration of intermediate de-risking technology development steps.

Some concept architectures only work practically in GEO orbit, while others can take advantage of different orbits to offer different solutions and more viable intermediate development steps. These could potentially be made to provide affordable energy, which may be a useful consideration when considering access to development funding.

3.1.2.2 Specific Power

The SBSP satellites, though very sparse structures, have a mass of several thousand tonnes. The production and deployment cost is strongly influenced by their mass, as is the cost of space launch. The specific power of the satellite will therefore be a strong determinant of the Levelised Cost Of Electricity (LCOE). Factors such as optimal use of mirrors and very high concentration PV can significantly reduce the mass of the PV collector sub-system. All three concepts choose different solutions to optimise the specific power.

3.1.2.3 Thermal Management

The electrical power transmission and distribution across the satellite from collector to transmitter is a major design consideration, both to manage the thermal aspects, and minimise the system mass. Keeping component temperatures within acceptable limits is important to achieve the required system life. This is a particular challenge for systems in space as there is no fluid present to convect heat away from the satellite.

3.1.2.4 Attitude and orbit control

In common with all satellites the SBSP satellites will need a system to keep it in its precise orbit and maintain its pointing direction. With the drive to minimise mass (and hence cost), the concept needs to maintain accurate pointing accuracy and orbit control whilst minimising the need for reaction control propellant.

3.1.2.5 Functional orbit

This study uses the term “functional orbit” as a generic term to describe where the satellite generates power to recognise that there are a broad range of potential orbits that might be utilised to deliver an SBSP capability.

The orbit that is selected will be a result of the system architecture, the cost of raising the satellite to that orbit, the availability of a slot in the orbit and the risk presented both by the satellite, and to the satellite, from other objects. As the launch cost is likely to be a key driver of cost, the orbit can potentially have a significant influence on LCOE.

The designs considered in this study can all operate in GEO to deliver base load power, with some alternatives being proposed by the designers. Nonetheless there are some studies that have gone into great depth to understand the possibilities and influence of alternative orbits (McNally, 2018).

3.1.3 Satellite supportability and design life

Most studies assume an operational life of around 30 years, which is a long time in the harsh radiation and thermal environment of GEO. With such a large cost to develop, manufacture and deploy the system, the satellite life is a dominant factor in the LCOE and is currently only assumed. At the current level of development of the systems design life has been set as a target, further development will be required to understand the impact of this target on the design of the systems.

As the through-life supportability solutions for the designs are currently very immature, supportability has been considered by:

- Assuming a flat operating expenditure (OPEX) through life, as a percentage of capital expenditure (CAPEX) to allow for periodic robotic maintenance missions to replace or repair defective components (Mankins, 2017).

- Oversizing the satellite during commissioning to allow for an assumed failure rate through life, delivering the same net energy as a system designed to maintain its availability (Cash, 2017).

The supportability solution is a key factor driving all contributors to LCOE and is currently based on assumptions. This requires development to gain confidence in the solution and its LCOE implications.

3.1.4 Wireless Power Transmission Frequency

The optimum choice of power beaming frequency is one consideration in the trade-off between the satellite orbit, satellite sizing, power level transmitted, power beaming efficiency, the transmitter diameter and receiver diameter, the thermal limits on the sandwich panel (which fixes the ratio of solar to RF aperture), and the upper safe limit of Radio Frequency (RF) intensity at the centre of the received beam. Diffraction physics dictates that, at a given beaming distance, the higher the frequency the smaller the spot diameter on the ground becomes for a given satellite transmitter size. As frequency increases the power intensity also increases, when keeping the power, beaming distance and spot diameters constant (Cash, 2020).

The atmospheric window to minimise transmission losses means a frequency between 1GHz and 10GHz are the practical limits. Most SBSP studies have therefore looked at 2 frequencies within this band, 2.45GHz and 5.8GHz, which are ISM band frequencies, reserved for Industrial, Scientific and Medical use, as these are more likely to be adopted for SBSP (Kalpana Chaudhary, 2018).

Other factors to consider include the inherent efficiency and power density that can be achieved in the power electronics used in the wireless power transmission and reception. This will be affected by the choice of semi-conductor base material and architecture and will depend on the operating frequency.

One study concludes that "… it has been found that microwave power transfer at 5.8-GHz frequency has a size reduction advantage over 2.45 GHz in SSPS. However, this is valid up to the unit size of 1 GW only. Where more than 1 GW unit modules are employed there are feasibility restrictions established for the microwave transmission structure and the design of high power antenna phased array network is found to be impractical." (Kalpana Chaudhary, 2018)

In summary, 2.45GHz has been chosen for larger (2GW) systems, whilst 5.8GHz may be optimal for lower power, lower mass systems.

3.1.5 Design for demise

Increasingly it is a regulatory and ethical requirement, to have a plan for the satellite end of life before gaining permission to launch. Parking the satellite in a "graveyard orbit" is likely to be viewed as unsustainable. Little study has been made of this problem for such large structures in space. Outline concepts include re-working and re-purposing the valuable materials either in orbit or transporting them to the moon, or de-orbiting the satellite to Low Earth Orbit (LEO) and from there transporting the modules back to Earth.

3.1.6 Mission flexibility

The satellite configuration is tailored to the intended orbit, such as GEO, to maximise the utilisation and power delivery through the whole orbit. Some of the SBSP concepts are by their design limited to a GEO orbit, others are more flexible and could utilise different orbits, such as a constellation in an elliptical orbit, and still achieve high utilisation, and therefore provide affordable energy. This capability may offer mission flexibility and the opportunity for smaller scale development satellites to providing energy for other applications (e.g. research organisations in Polar Regions where the cost of fuel is very high, disaster relief, military deployments).

3.1.7 Other challenges

There are many other technical challenges common to SBSP concepts, such as achieving the necessary wireless power transmission (WPT) conversion efficiency, developing the ultra-lightweight structures, managing the structural dynamics of the huge structure, the likely requirement for robotic assembly in orbit, raising the orbit with high specific impulse (I_{sp}) propulsion, avoiding the Van Allen radiation belts, and being tolerant to debris and micro-meteorite damage.

3.2 CONSTANT APERTURE SOLID-STATE INTEGRATED ORBITAL PHASED ARRAY (CASSIOPEIA)

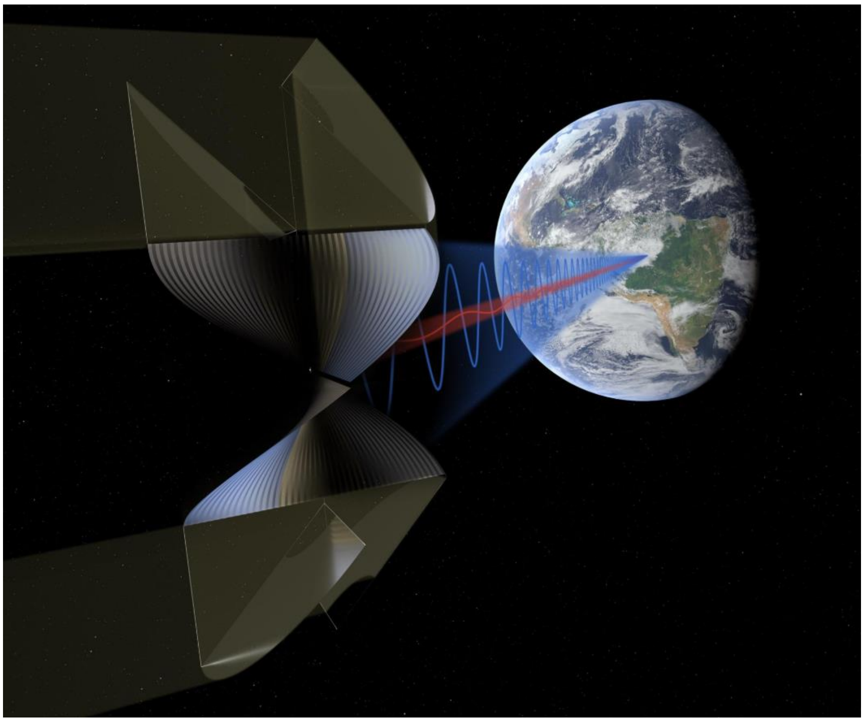

Figure 2 – Rendering of CASSIOPeiA in space with superimposed pilot beam and microwave power transmission

CASSIOPeiA consists of a helical structure with High Concentration solar Photovoltaic (HCPV) panels oriented to face North/South to collect light reflected off of mirrors at either end of the structure. The HCPV panels are orthogonal to a series of microwave emitting antennae forming an orientable phased array. This allows the microwave beam to be steered through 360°. As a result the mirrors can remain orientated to face the Sun at all times during its orbit whilst delivering constant power to Earth (Cash, 2019). This feature also allows it to function in a wide variety of orbits, removing the conflict between Earth pointing and Sun facing parts of the structure and the constraints of angular momentum in non-circular orbits.

The system is fully solid state, with no moving parts. In orbit stabilisation is achieved by modulating the solar pressure on the mirrors with electro-chromic film.

It is a modular distributed design, with individual modules comprising combined PV and RF dipoles. It is assembled from a very large quantity of just 5 standard module types, which could aid deployment and robotic assembly. The distributed design is intended to minimise the power distribution and associated thermal management challenges. It also allows for graceful degradation by removing single points of failure. The designer envisages that the satellite would be maintenance free, with an allowance for graceful degradation over the lifespan.

For a 2GW system, the estimated mass is 2,000 tonnes with an antenna of 1.6km diameter (Cash, 2019) beaming to a 5km wide rectenna. This is expected to have a high specific power rating, made possible because the configuration employs HCPV, reducing the area of PV required, and the innovative layout gives high utilisation of all of the modules.

3.3 SOLAR POWER SATELLITE VIA ARBITRARILY LARGE PHASED ARRAY (SPS-ALPHA)

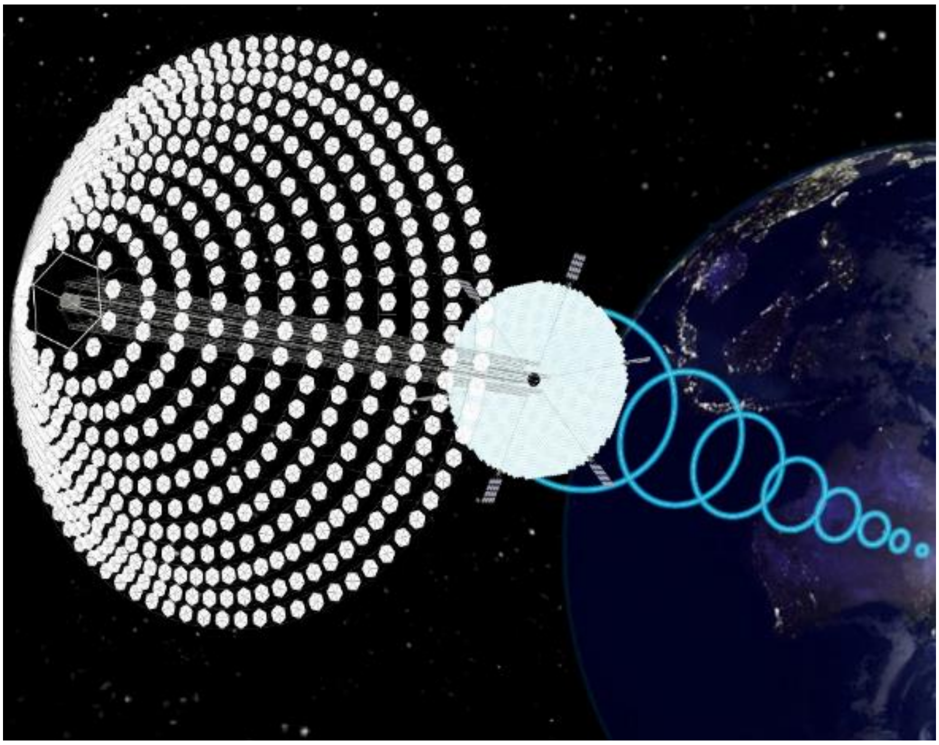

Figure 3 – Rendering of SPS ALPHA in space with superimposed microwave power transmission (Mankins, 2017)

SPS-ALPHA is a Sun-pointing concentrator design, using a gravity gradient stabilised structure to separate the mass of the mirrors from the larger mass of the sandwich panel by several kilometres. The sandwich panel works in a similar way to that on CASSIOPeiA but is permanently pointing towards Earth for power beaming. The reflectors in this design are heliostats, i.e. they are motorised and independently adjusted with the relative change in position to the Sun to reflect light onto the photovoltaics in the sandwich panel. This allows the satellite operator to control the amount of light hitting the panels by changing the position of the heliostats, which is useful to control thermal loads (Mankins, 2017).

SPS-ALPHA is a distributed modular design, assembled from a very large quantity of less than ten standard module types, which could aid deployment, robotic assembly and maintenance. This design also allows for graceful degradation by removing single points of failure.

The concept delivers 2GW of microwave power through a 1.7km diameter antenna paired with a 6km wide rectenna. The estimated mass is 8,000 tonnes (Frazer-Nash Consultancy, 2020). The satellite is designed to operate from GEO to ensure power is delivered to the same location. It is estimated that the design will have a 100 year lifespan, using its modularity to conduct component swaps if a fault occurs (Mankins, 2017).

3.4 MULTI-ROTARY SOLAR POWER SATELLITE (MR-SPS)

Figure 4 – Rendering of MR-SPS in space showing antenna and panels supported by rotating joints (Xinbin, et al., 2016)

MR-SPS is a Sun-pointing non-concentrator design. The satellite comprises large solar panels, supported at each side with a rotating joint (hence ‘multi-rotary’). The structure is then connected to an antenna. The rotating joints allow the solar panels to rotate independently of the structure in one axis (Xinbin, et al., 2016). The electricity generated in the solar panels is passed through the rotating joints to the antenna. The advantage of this concept is said to be in avoiding the challenge of engineering the precision solar concentrator system and thermal control. However the designers recognise that the extremely high power rotary joint and the lengthy electrical power distribution system are major technical challenges. Considerable thought appears to have gone into addressing these challenges.

The current design for 1GW is an 11.8km wide structure with a mass of 10,000 tonnes in GEO. The antenna has a 1km diameter and rectenna 5km wide (Xinbin, et al., 2016). The estimated life span is 30 years.

3.5 REVIEW OF CONCEPTS

3.5.1 Comparison Criteria

The criteria used to qualitatively compare the three concepts are described in **Table 1** below.

Comparison between SBSP Designs		
Criterion	**Description**	**Units (where relevant)**
Levelised Cost Of Energy	The total cost of building, operating and decommissioning an asset, per unit of total electricity generated over an assumed lifetime.	£/MWh
Specific power	The amount of rated power that can be delivered for a given system mass.	kW/kg

Table 1: Comparison criteria for SBSP designs

3.5.2 Technology assumptions

All concepts have benefited from extensive conceptual design studies and sizing, and they address the key engineering challenges with different innovative approaches. They propose to use current space-rated materials and component performance, albeit some of these are not yet available in the necessary volume or at the required price point. None of the concepts are reliant on major technology breakthroughs for the performance claimed.

3.5.3 LCOE assumptions

The published values for LCOE are difficult to compare, as each of the designers appears to have used different assumptions around (for example) space launch costs to LEO and GEO, production costs and learning curves, inclusion of back-up storage for the eclipse periods, maintenance, reliability and life. Additionally no correction has been performed for inflation. Costs will be explored further in Phase 2.

3.5.4 Validating the designs

All concepts are at a comparatively early conceptual design stage. They address the technical challenges in different ways, and as a result will have a different mix of technical risks to address. For a UK SBSP capability a detailed systems engineering Front End Engineering Design (FEED), and technology demonstration activities will be important next steps to validate the design claims and have confidence in the design to pursue.

The table below presents a high-level summary of the three SBSP designs, based on the reported values against criteria defined above. The information is sourced from the references at the top of the columns.

Summary of SBSP concept metrics			
Criterion	**CASSIOPeiA** (Cash, 2019)	**SPS-ALPHA** (Mankins, 2017) (Frazer-Nash Consultancy, 2020)	**MR-SPS** (Xinbin, et al., 2016)
Levelised Cost Of Energy (p/kWh)	£48/MWh	Initially £77/MWh, falling to £31/MWh	£230/MWh

Summary of SBSP concept metrics			
Criterion	**CASSIOPeiA** (Cash, 2019)	**SPS-ALPHA** (Mankins, 2017) (Frazer-Nash Consultancy, 2020)	**MR-SPS** (Xinbin, et al., 2016)
Capital costs (CAPEX) (scaled linearly to 2GW)	£7.8B	£8.1B	£21.7B
Operating and maintenance costs (scaled linearly to 2GW, annual)	Graceful degradation (i.e. loss of power but no maintenance cost)	3% of CAPEX = £243m/yr	£7.38 billion over 30 years = £246m/yr
Specific power (kW/kg)	2,000 tonnes for 2GW = 1kW/kg	8,000 tonnes for 2GW = 0.25kW/kg	10,000 tonnes for 1GW = 0.1kW/kg

Table 2 – Summary metrics for three leading SBSP designs

4. SYSTEM ENGINEERING FEASIBILITY ASSESSMENT

This section outlines the feasibility assessment performed to understand the Technology Readiness Levels (TRLs) of SBSP subsystems, what major engineering barriers need to be overcome and whether they can be addressed technically by 2050. We consider this both at the subsystem level, as well as at the whole system level.

4.1 ENGINEERING FEASIBILITY CHARACTERISTICS

4.1.1 Feasibility Definition

This study has focussed on the high-level engineering feasibility of developing SBSP in a time frame that would allow it to support Net Zero. This has been done by considering:

- The technological development required prior to 2050, considering the Technology Readiness Level (TRL).
- The major engineering barriers, in terms of what else is required to realise a system other than sufficient understanding of the technology. This includes factors such as sufficient manufacturing capacity and sufficient launch capacity.
- The relative level of difficulty expected in achieving the technological development required prior to 2050 given the current understanding and scalability challenges.

These are defined further in the following sections. This study has developed an understanding of the barriers and the time and steps required to overcome them through the development of a roadmap (Section 6). By reviewing the necessary roadmap we have been able to come to a judgement as to whether SBSP is feasible from an engineering perspective in order to support Net Zero.

It has been assumed that there are no other barriers in place, i.e. economic or financial, social, political, legal or environmental.

4.1.2 Technology Readiness Levels

Technology Readiness Levels (TRLs) provide a scale to compare the relative maturity of the technologies required to realise a system, and therefore provide a measure of the level of technical risk present. The TRLs we have used are defined in Annex A.

4.1.3 Major Engineering Barriers

In addition to the TRL we have also considered the major engineering barriers that must be overcome to realise the system. Using a systems approach we have developed definitions of the key engineering barriers, derived as the opposite of the system enablers described below.

Enabler	Enabler Description	Example of Barrier
Raw material	Enough material present to realise the subsystems.	Shortage of material due to scarcity (e.g. a lack of rare-earth element)
Technology	The scientific principles are understood in order to deliver a subsystem that can perform the function, to the desired performance, in the given environment.	Particular technology development step

Enabler	Enabler Description	Example of Barrier
Production facilities	Facilities to convert raw material to the Whole System and validate. There is sufficient manufacturing capability, in order to convert the raw materials into the designed system, in the given time frame to the target quality. Ability to test and integrate the components, subsystems and system.	Insufficient production/ test/ integration facilities.
Infrastructure	Underlying systems to move resources, material, components and assemblies throughout the lifecycle.	Insufficient Earth/ space lift / LEO to GEO systems

Table 3: Enablers, and their corresponding barrier definitions

4.1.4 Level of Difficulty

This criteria assesses the difficulty in achieving the required levels of development. This is related to, but not solely dependent on, the current TRL and reflects the potential challenges in both maturing technology and scaling it.

Level	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 mature 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 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 in related fields.
Extreme	There is not a clear development path to mature the technology. Significant breakthroughs will be required. Further work is required to establish the viability of the technology.

Table 4: Difficulty levels, and their definitions

4.2 SUBSYSTEM FEASIBILITY SUMMARY

Figure 5 and Table 5 below provides a summary of the inputs to the technology feasibility assessment TRLs and major engineering barriers, for the UK and internationally, for each subsystem. For full information see Annex B.

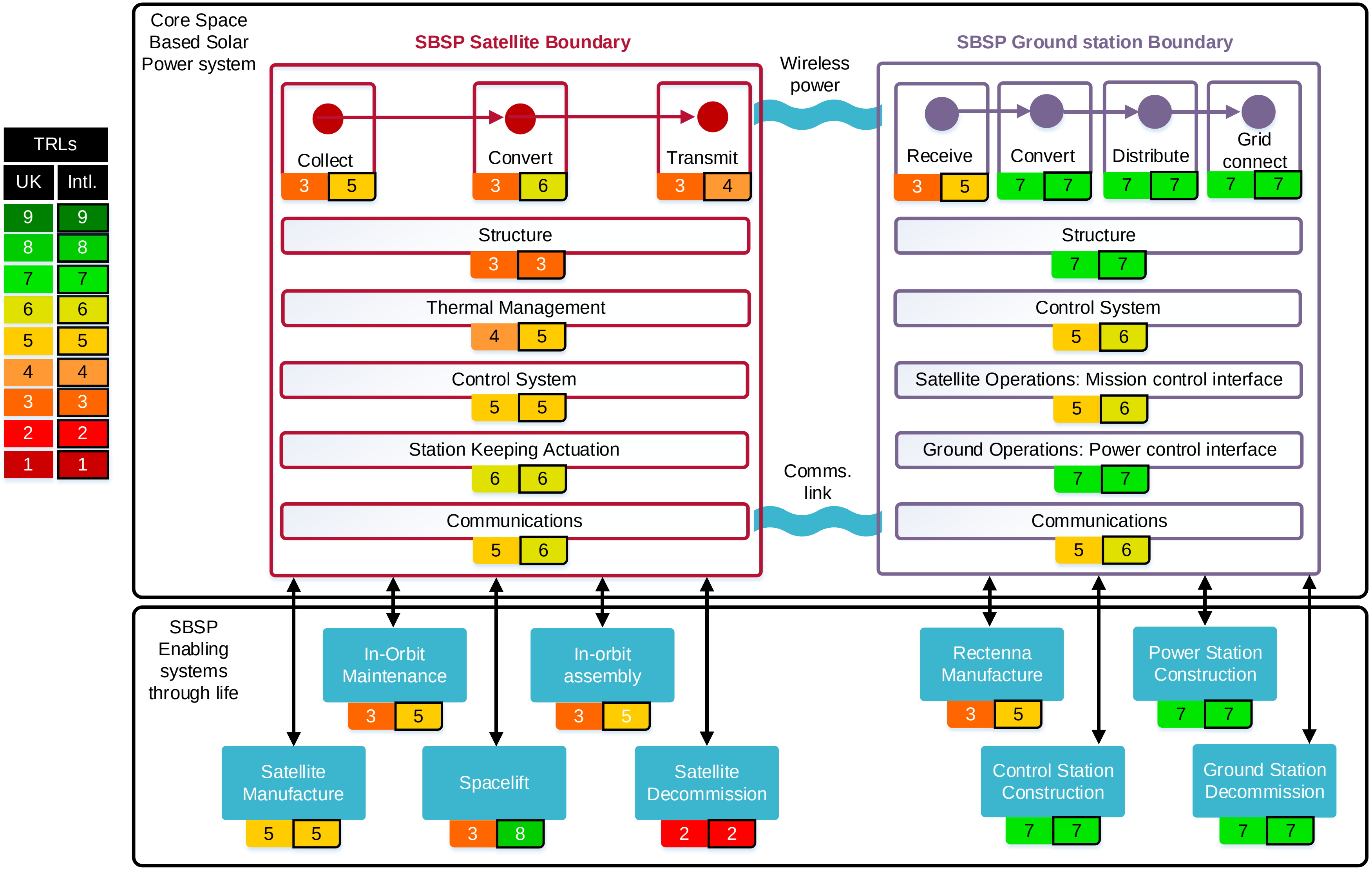

Figure 5: Visual summary of subsystem TRL assessment

Subsystem element name	Critical technology	UK TRL	UK major barrier	Inter. TRL	International major barrier	Technically feasible by 2050?	Level of Difficulty
Satellite collect	Large (km scale) mirror in space	3	Experience of manufacturing large reflective surfaces for use in space.	5	Manufacturing capacity for large reflective surfaces in space.	Yes	High
Satellite convert	High efficiency space photovoltaics (PV) and power electronics	3	Manufacturing capacity for solar panels for space.	6	Technology development of High Capacity Solar Panel (HCPV) is required to reduce mass and increase efficiency.	Yes	Medium
Satellite transmit	Microwave power beam transmission at scale	3	Experience manufacturing large, efficient, power transfer antennas.	4	Technology is inefficient at small scale so difficult to test, some testing has been conducted however further work is required to prove high efficiencies and accuracies necessary for space based solar power.	Yes	Very High
Satellite thermal management	Space power electronics cooling	4	Uncertain system architecture/design results in uncertain cooling requirements and whether an active cooling system is required.	5	Uncertain system architecture/design results in uncertain cooling requirements and whether an active cooling system is required.	Yes	Medium

Subsystem element name	Critical technology	UK TRL	UK major barrier	Inter. TRL	International major barrier	Technically feasible by 2050?	Level of Difficulty
Satellite structure	Lightweight large scale structures in space	3	Advances in designing large scale structures to be constructed and assembled in space are required.	3	Advances in designing large scale structures to be constructed and assembled in space are required.	Yes	Very High
Satellite station keeping	Electric thrusters	6	Scalability of existing technology to be applicable to a large lightweight structure. Encompassing the use of electric thrusters and mechanical damping required to provide station keeping while minimising structural mass.	6	Scalability of existing technology to be applicable to a large lightweight structure. Encompassing the use of electric thrusters and mechanical damping required to provide station keeping while minimising structural mass.	Yes	High
Satellite control system	Integrated control system of sensors, processing and control logic	5	New control systems for large satellites with significant area for photon pressure will need to be developed. This will require enhanced understanding of the behaviour of very large structures in space.	5	New control systems for large satellites with significant area for photon pressure will need to be developed. This will require enhanced understanding of the behaviour of very large structures in space.	Yes	Medium
Satellite communications	Space telemetry link	5	More robust communication required due to criticality for national energy supply.	6	Must be allocated frequency bands and agree at international level to avoid inference with other technologies.	Yes	Low

Subsystem element name	Critical technology	UK TRL	UK major barrier	Inter. TRL	International major barrier	Technically feasible by 2050?	Level of Difficulty
Ground receive	Rectenna for power conversion	3	Limited understanding and experience of rectenna technology.	5	Due to diffraction physics there is a link between the size of the satellite antenna and the size of the rectenna on Earth. To minimise the size of the satellite the rectenna area required on Earth is large. A smaller rectenna could be used, but only a fraction of the power beamed would be captured, however this would still demonstrate the physics.	Yes	High
Ground convert	Electrical inverter	7	No significant engineering barriers.	7	No significant engineering barriers.	Yes	Low
Ground distribute	Transformers and cable	7	No significant engineering barriers.	7	No significant engineering barriers.	Yes	Very Low
Ground structure	Terrestrial structures	7	Uncertainty over the design requirements for the ground structure, i.e. how large a ground area needs to be committed to the SBSP ground station – how much of a clear zone is required around the rectenna.	7	Uncertainty over the design requirements for the ground structure, i.e. how large a ground area needs to be committed to the SBSP ground station – how much of a clear zone is required around the rectenna.	Yes	Low
Ground grid connection	Grid interface monitoring and switch	7	No significant engineering barriers.	7	No significant engineering barriers.	Yes	Very Low

Subsystem element name	Critical technology	UK TRL	UK major barrier	Inter. TRL	International major barrier	Technically feasible by 2050?	Level of Difficulty
Ground control system	Integrated control system of sensors, processing and control logic	5	Limited experience in the control of large satellites critical to national infrastructure.	6	No experience controlling satellites on the scale proposed and associated additional control mechanism that may be required.	Yes	Medium
Ground communications	Space telemetry link	5	Limited experience communicating with satellites critical to national infrastructure.	6	No experience of creating a cohesive communication link between national grid requirements and satellite operations.	Yes	Low
Satellite operation	Satellite control system interface	5	A more complex interface will be required and this will likely bring additional engineering challenges to maintain control over a large satellite of national significance.	6	Integration of control interface with power grid.	Yes	Medium
Satellite maintenance	Remotely operated/ Automated/ autonomous space robotics and rendezvous in orbit	3	Limited experience operating robotics in space.	5	Level of autonomy in robots is currently likely to be insufficient to contact maintenance without human intervention and the associated communication complexities.	Yes	Very High
Power station operation	Ground station control interface	7	Incorporating a new type of grid input technology to the national energy mix.	7	Incorporating a new type of grid input technology to the national energy mix.	Yes	Low

Subsystem element name	Critical technology	UK TRL	UK major barrier	Inter. TRL	International major barrier	Technically feasible by 2050?	Level of Difficulty
Satellite manufacture (ground)	Satellite manufacture	5	Capacity for mass production of space grade parts.	5	Capacity for mass production of space grade parts.	Yes	High
Space lift	Heavy lift space launch	3	Extremely limited experience with space launch and large space programmes compared to other nations.	8	Current lack of capacity to launch the volume and mass required.	Yes	High
In-orbit assembly	Remotely operated/ automated/ autonomous space robotics	3	Limited experience operating robotics in space.	5	Challenges of modular assembly while retaining structural stiffness.	Yes	Very High
Satellite decommission	To be defined	2	There is no clear method established for decommissioning satellites in space.	2	There is no clear method established for decommissioning satellites in space.	Yes	Very High
Rectenna manufacture	Rectenna manufacture	3	UK has very limited experience in rectenna manufacture which would need to be done at scale to achieve the size of rectenna required.	5	Scale of production would need to significantly increase while maintaining quality standards.	Yes	Medium
Power facility construction	Power facility station construction	7	No significant engineering barriers.	7	No significant engineering barriers.	Yes	Low

Subsystem element name	Critical technology	UK TRL	UK major barrier	Inter. TRL	International major barrier	Technically feasible by 2050?	Level of Difficulty
Control station construction	Control and communication facility construction	5	No significant engineering barriers.	6	No significant engineering barriers.	Yes	Low
Ground station decommissioning	Terrestrial systems decommissioning	7	No significant engineering barriers.	7	No significant engineering barriers.	Yes	Low

Table 5: Summary of TRL, barriers and feasibility assessment

4.3 WHOLE SYSTEM CONSIDERATIONS

This section discusses issues which affect the SBSP system as a whole which have been raised by project stakeholders and published by objectors.

4.3.1 Stakeholder Considerations

In addition to considering the feasibility of the subsystems required for SBSP throughout its life, the stakeholders raised a number of whole system considerations for SBSP. These are discussed below. None of the issues raised present a fundamental barrier to engineering feasibility but they will be the subject of ongoing assessment.

Electromagnetic Interference (EMI): Transmitting large amounts of power via microwave has the potential to cause electromagnetic interference (EMI) to other electronic devices in the vicinity of the beam. Our Subject Matter Expert judgement is that, at the levels of energy flux being suggested (230W/m^2), this will likely interfere with electronic devices within the path of the beam, however it is unlikely to significantly influence devices outside of the perimeter of the SBSP ground site. It may be necessary to have no-fly zones in the path of the beam extending through the stratosphere into the Class A airspace and airways. This will require testing and trialling throughout SBSP's development and will be the subject of international regulation and approval.

Environmental concerns over atmospheric heating: The operating frequencies of the microwave beam are chosen so to minimise the losses in the atmosphere. Even on days with high precipitation the losses are less than 2% (Kantak, 2014). In our stakeholder engagement there was a subjective view that this would lead to a negligible effect on the atmosphere (Frazer-Nash Consultancy, 2020).

Ionospheric Scintillation: The microwave beam could be sensitive to ionospheric scintillation, i.e. rapid variations in signal amplitude and phase generated when there are significant irregularities in the ionosphere. These are known to diffract and scatter radio signals. It is a radio analogue to the twinkling of starlight by turbulence in the troposphere. S-band (2-3 GHz) signals from satellites are less prone to scintillation than VHF, UHF and L-band satellite signals, but the European Space Agency (ESA) have had occasional but significant scintillation issues on Cluster with downlink at 2.1 to 2.3 GHz. They have reported that in normal conditions, such scintillation is mainly a problem at low-latitudes during evening hours (as ESA had with Cluster downlink to their ground station in the Canaries), and high latitudes at any local time. But it may well become a mid-latitude problem during active space weather conditions. There may also be an issue during total and partial solar eclipses as these lead to sharper than usual changes in solar irradiance and hence sharper gradients in the ionosphere (Mutlow, 2020).

Ground heating: The overall efficiency of the SBSP ground station, including the proportion of microwave beam energy captured, rectenna efficiency and power conversion efficiency, is estimated to be of the order of 70% (Vinogradova, 2017). This compares very favourably with the efficiency of other power stations, for example the thermal efficiency of nuclear power stations is 40% or less (Sönnichsen, 2020). This means that a SBSP station with a 2GW output potentially releases about 0.85GW of heat to the environment while a similar nuclear plant releases around 3GW of heat.

System security: As Critical National Infrastructure (CNI) it will be important for SBSP to be secured against potential threats. High-level threats are likely to include cyber-attacks to either deny and/or steal power, or alternatively malicious damage to the system. There is already significant work ongoing in the UK to protect CNI against cyber-attack and this work could be used to inform the designs of SBSP.

Debris withstand: The growing orbital debris problem is a risk for any spacecraft. For SBSP, the risk of damage from orbital debris impact may be mitigated by both the choice of orbit, and the design of the modular and distributed architecture of the satellite.

Satellites/spacecraft crossing: There is the potential for SBSP satellites to work in higher orbits. As such other satellites may pass through the microwave transmission beam. If there is a risk that the beam would cause damage it is possible to turn the beam off for during the transit. The interference/damage risk would need to be determined and mitigated as part of SBSP's development.

Orbital Congestion: The functional orbit used for a realised SBSP system is a factor that requires further investigation as there are a wide variety of options depending on the system architecture and concept of operation (McNally, 2018). The functional orbit adopted affects both the cost of launch (and therefore LCOE) as well as the feasibility of the concept due to its influence/risk to other space assets. Two of the reference designs considered (SPS-ALPHA and MR-SPS) rely on the use of GEO, while CASSIOPeiA does not. Congestion in GEO has been a recognised issue since the 1960s and is managed by the International Telecommunications Union (ITU) (Matignon, 2019). Currently there are 535 satellites recorded in GEO (Johnston, 2020), with potential slots for 1800 (Billing, 2017). It has been predicted that congestion in GEO will double within 50 years (Schaub, 2014). This would suggest that, even if GEO is to be used for the satellite, that there should be slots that could be allocated to SBSP for the 5 satellite architecture used in this study.

4.3.2 Review of Objections to SBSP

This sections reviews key objections to SBSP to understand whether they identify additional engineering barriers. In addition to the engineering barriers raised there is a common view is that SBSP is too expensive, due to many contributing factors (Handmer, 2019) (Handmer, 2019).

- **Engineering Objection:** One article mentions the large ground area required (Murphy, 2012) which aligns with our findings in Section 5. The rectenna needs to have a contiguous area of the order of 5km diameter taken from 230W/m^2 for 2GW in order to deliver 2GW to the grid. This leads to a power density which is lower than fuelled plant, such as gas and nuclear, but higher power density than terrestrial renewables (Section 5.2.8).
    - **Response:** We agree that finding a land area to support SBSP rectennas is a significant challenge. It is not clear where it would be feasible to construct them in the UK and this would be a key aspect for more in-depth study. SBSP proponents have suggested that land used for rectennas could also be used for other purposes (such as farming/forestry) however it is currently unproven if this is achievable. Alternatives also include net-like rectenna raised over farmland/access roads or deploying the rectennas offshore, although this would require significant technical development. Due to the elevation of a SBSP satellite in GEO when seen from the Earth, the rectenna will need to collect power over an elliptical area. For a 5km wide antenna in the UK the major axis of the rectenna will be over 10km.
- **Engineering Objection:** One article identifies a risk around managing the safety of the microwave beam (Murphy, 2012), however also notes that there is little concern about the beam accuracy and that the proposed level of 230W/m^2 (Cash, 2017) is thought to be safe for birds and aircraft to fly through.

  - **Response:** We agree that there is a risk present around the safety of the beam, however this is likely to be possible through appropriate design. It is likely that the beam would be a “no-fly zone” for aircraft, although such no-fly zones already exist around current nuclear power plants (Civil Aviation, 2016).
- **Engineering Objection:** One article from 2015 (DangerOnion, 2015) identifies that the capacity to launch material into space is insufficient, stating that, to replace Japan’s power supply, “Imagine we can build and launch one Delta IV Heavy rocket, the only one capable of such a task, every day. We can’t. We’ve only launched eight in the last eleven years…. it would take a hundred and forty-two years**”**
  - **Response:** We agree that having sufficient launch capacity is a challenge, however:
    - For this study we are focussing on delivering 10GW of SPSP, not 45GW.
    - When referring to 2050 timeframes the industry stakeholders we have engaged with have argued that it is feasible for there to be sufficient launch capacity for the capability this study is considering (10GW).
    - There has been an increase in launch capacity since 2015. China has gone from 18 annual launches in 2015 to a maximum of 38, India from 5 to a maximum of 7, the US from 18 to a maximum of 34 and others from 13 to a maximum of 15 (Aerospace Security, 2020).
- **Engineering Objection:** SBSP has a low efficiency. It can have greater solar energy incident on it, but that has to go through a “double conversion… from photon to electron to photon back to electron…there are two conversions you don’t have to do on Earth” such that would negate the benefit of sending the solar PV to space (Musk, 2012).
  - **Response:** The efficiency of an energy system does not influence whether it is feasible from an engineering perspective, with the exception of noting whether the system will generate less power than is required to manufacture it over its lifetime. As stated in Section 5.2.7, SBSP systems have been suggested to repay their energy in 4.8 months of operation. Efficiency will drive the cost of the system.

4.4 ENGINEERING FEASIBILITY SUMMARY

In summary we have found that there are some significant challenges to be overcome, however it appears feasible to overcome all of them by 2050.

Considering the Whole System View from Section 2 we have assessed TRLs and barriers against the constituent subsystems. The key engineering barriers to achieving SBSP in order to support Net Zero in 2050 are:

- Technology maturation across all subsystems. The most immature aspect is decommissioning the satellite. Other subsystems requiring significant development are the energy subsystems on the satellite, structural and control subsystems, in-orbit assembly and maintenance robotics.
- Sufficient production facilities to manufacture the satellites.
- Sufficient launch capability to deliver the satellites to their operational orbits.

Additionally considering whole system engineering barriers, these are:

- Sufficient surface area to deploy the rectennas – they may require deployment at sea which incurs additional technical and environmental risk.

- System security and debris damage withstand.
- There is a potential risk of material shortages for the manufacture of the solar photovoltaic technology currently being pursued.

5. SBSP AS PART OF THE UK ENERGY MIX

5.1 OVERVIEW

This section compares SBSP against other low carbon energy technologies both in isolation and as part of an energy mix. The aim is to demonstrate the comparative characteristics of SBSP and to understand the type of impact it might have on the performance of the future electricity grid. Both the technologies considered, and the scenario considered, are developed from the Energy System Catapult's work on Innovating to Net Zero (Energy Systems Catapult, 2020).

5.2 SBSP COMPARED AGAINST OTHER LOW CARBON TECHNOLOGIES

This section compares SBSP against other low carbon technologies in isolation. Table 8 below presents the comparison across the criteria in **Table 6** and assigns a red/amber/green to the property based on the literature reviewed and SME judgement.

SBSP vs other low carbon technologies		
Criterion	**Description**	**Units (where relevant)**
Levelised Cost Of Energy	The total cost of building, operating and decommissioning an asset, per unit of total electricity generated over an assumed lifetime.	£/MWh
Intermittency (ability to "baseload")	The variability of the power available over a given time interval. For this study the variation daily.	%
Firm capacity	The fraction of rated power which is available at peak demand.	%
Predictability	The level of confidence that can be assigned to an expected level of power output in the future.	%
Dispatchability	How quickly the technology can deliver its rated power to the grid in response to a demand signal.	seconds
Grid operability	How well does the technology contribute to the operation of an effective electricity network, considering inertia, voltage control and reactive power.	-
Lifecycle carbon per unit energy	The amount of CO_2 emitted over the life cycle of an energy technology (considering material extraction to disposal) compared to the expected amount of energy generated over its life.	gCO_2/kWh
Land power density	The amount of rated power that a generation technology can contribute to the grid compared to the area required on the Earth's surface to deliver (land or sea).	kW/m^2

Table 6: Comparisons criteria for low carbon technologies

5.2.1 LCOE

Table 8 below records SBSP as “amber” compared to other generation technologies, this is to represent the significant uncertainty in the values reported at this time.

The costs used for comparison to SBSP are derived from the longest term predictions from BEIS, resulting in costs in 2030 (BEIS, 2016). As SBSP is a developing technology there is significant uncertainty in the cost of realisation due to the assumptions in place, considering factors such as the operational life of the system and the cost of space lift in the future. Some papers argue that SBSP may be significantly cheaper than alternative sources of energy (Cash, 2019), while other present the sensitivity to present assumptions that would lead to costs comparable to current energy sources (Mankins, 2017) (Madonna, 2018).

These values are based on the LCOE claimed by proponents of SBSP and will be interrogated further in Phase 2 of this work. Immature energy technologies are likely to produce estimates that are inaccurate compared to the final costs due to the learning, research and development that needs to take place.

5.2.2 Firm Capacity

Table 8 below shows that SBSP has a higher firm capacity compared to wind, terrestrial solar PV and batteries, the other technologies considered, and can therefore be more strongly relied on during grid “stress events”. This is based on SME judgement given that the concept considered has low intermittency, and is therefore comparable to fossil fuelled/nuclear plant.

For comparison, National Grid has proposed methodologies as to the de-rating of many renewable energy technologies, i.e. the power that can be relied on from a given installation compared to its rated power during a “stress event”. Terrestrial Solar PV and Battery Storage both have significant de-rating with only around 1-2% being available for both (National Grid ESO, 2019). As SBSP has very low intermittency when placed in GEO it will likely have a firm capacity closer to that of nuclear and gas stations.

5.2.3 Intermittency

Table 8 below shows that SBSP has lower intermittency than wind and terrestrial solar PV and is comparable to technologies using fuel. This is based on SME judgement given that the concept considered is able to deliver power almost continuously.

SBSP would generate continuously with the exception of a 70 minute interruption at the spring and autumn equinox, as well as shorter interruptions of a few days either side of the equinox. While a significant power loss (all SBSP attached to the grid would go offline), it is highly predictable years in advance.

Combining information available from BEIS (BEIS, 2016) on average load factor and reports on historical generation (Templar, n.d.), (Elexon, 2020) shows the intermittency of generation technologies. For those technologies which can generate based on fuel availability we have allocated them a “green” status – i.e. should there be sufficient fuel then they would be able to generate continuously until either a failure or until a scheduled maintenance.

5.2.4 Predictability

Table 8 below shows that SBSP has higher predictability than wind and terrestrial solar PV and is comparable to technologies using fuel. This is based on SME judgement given that the concept considered is able to deliver power almost continuously.

We have allocated the assessment of predictability based on reports of historical generation (Templar, n.d.), (Elexon, 2020) and SME judgement. For those technologies which can generate based on fuel availability we have allocated them a “green” status – i.e. based on the prediction of fuel provision then they would be able to generate as predicted until either a failure or until a scheduled maintenance.

5.2.5 Dispatchability

Table 8 below shows that SBSP has been allocated a high dispatchability. This is based on our assumption that the power produced from the satellite is near constant, and that it is possible for the ground station to use the electrical machinery to alter the amount of power delivered to grid quickly, based on its similarity to terrestrial solar PV equipment.

While the electrical machinery for SBSP is considered similar to that required for terrestrial solar PV, the reason it has a higher dispatchability is that the power is almost constantly available. In contrast, terrestrial solar PV output is strongly driven by the time of day, season and weather conditions, similar to wind. The other assessments of dispatchability are based on SME judgement and input from (Hanania, 2020).

5.2.6 Grid Operability

Table 8 below shows that SBSP has been allocated an assessment of “red” compared to the other technologies, similar to terrestrial solar PV. Grid operability includes factors such as reactive power management, voltage control and inertia. This is receiving increased interest as the amount of renewable energy sources is increasing. There is ongoing work to address these potential issues by National Grid (National Grid ESO, 2020).

Any generation that uses large rotating masses to generate electricity provides inertia to dampen variation in frequency on the grid and is beneficial. This arises from gas plant, biomass plant and nuclear plant. The inertia of wind turbines is generally lower and terrestrial solar PV and SBSP has negligible inertia.

Considering reactive power and voltage support this has largely been taken for granted on existing baseload plant such as nuclear and gas plant as it is implicit in their operation. Reactive power compensation is managed through the use of electrical machinery on wind and solar PV installations. It is therefore assumed that this would also be the case for SBSP, allowing SBSP to be used on the grid.

In summary, SBSP has similar grid operability characteristics to terrestrial solar PV in that it provides minimal to no inertia, and would likely require reactive power compensation.

5.2.7 Lifecycle Carbon Per Unit Energy

Table 8 below shows that SBSP has been assessed to be “green” for lifecycle carbon per unit energy. Considering initial estimates for SBSP of 20gCO_2/kWh (URSI Inter-commission Working Group on SPS, 2007) as well as energy payback times of 4.8 months (L. Summerer, 2005), suggests that it is comparable with published values for wind and nuclear (IPCC, 2014).

5.2.8 Land Power Density

Table 8 below shows that SBSP has been assessed to be “amber” compared to other technologies. SBSP designs currently target a maximum beam energy flux of 230 W/m^2, or 230MW/km^2 (Cash, 2019), resulting in a power density between that of other renewables (approximately 1-10MW/km^2) and fuelled technologies (approximately 1GW/km^2) (Mackay, 2008). SBSP proponents have suggested that land used for rectennas could also be used for other purposes (such as farming/forestry) however it is uncertain if this is achievable.

Assessment	Description
Green	Better performance or lower cost compared to alternatives
Amber	*Average/middling performance or cost compared to alternative*
Red	*Poorer performance or higher cost compared to alternatives.*

Table 7: Assessment description for technology comparison

Criterion	SBSP	Onshore Wind	Offshore wind	Terrestrial Solar PV	Nuclear	Dedicated biomass	Gas CCS
LCOE (BEIS, 2016), (Cash, 2019) **,** (Mankins, 2017) (Madonna, 2018)	Amber	Green	Amber	Green	Green	Amber	Amber
Firm capacity (National Grid ESO, 2019)**, (SME judgement)**	Green	Amber	Amber	Red	Green	Green	Green
Intermittency (BEIS, 2016)**, (SME judgement)**	Green	Red	Amber	Red	Green	Green	Green
Predictability (BEIS, 2016)**, (SME judgement)**	Green	Red	Amber	Red	Green	Green	Green
Dispatchability (Hanania, 2020)**, (SME judgement)**	Green	Red	Red	Red	Red	Amber	Green
Grid operability (SME judgement)	Red	Amber	Amber	Red	Green	Green	Green
Lifecycle carbon per unit energy (IPCC, 2014)**,** (L. Summerer, 2005)**,** (URSI Inter-commission Working Group on SPS, 2007)	Green	Green	Green	Amber	Green	Red	Amber
Land power density (Mackay, 2008)**,** (Cash, 2019)	Amber	Red	Red	Red	Green	Green	Green

Table 8: Comparison of SBSP against other potential Net Zero technologies

5.3 2050 ENERGY SUPPLY AND STORAGE SCENARIO COMPARISON

There are a wide range of scenarios posited for the future of the UK which consider variations in population growth, the level of investment, the level of decarbonisation achieved, the rate of technology adoption and the policies that are implemented.

The Energy Systems Catapult takes a whole system approach to understand the energy system, and considers generation as one aspect of it. It also considers the system in terms of electricity, heat and transport (Energy Systems Catapult, 2020). In addition to electricity, other energy vectors considered include hydrogen and district heat.

To support this first study into the feasibility of SBSP as a contributor to Net Zero we have used a baseline generation scenario for 2050 taken from the Energy System Catapult's document on Innovating to Net Zero.

For comparison we have developed an alternative scenario whereby an amount of the generation produced by other technologies has been replaced by SBSP. The comparison criteria are presented in **Table 9**.

Scenarios with and without SBSP		
Criterion	**Description**	**Units (where relevant)**
Average Cost Of Energy	The weighted average of the LCOE of all generation technologies contributing to the grid.	£/MWh
Grid firm capacity	The fraction of the sum of rated power across generation technologies which is available at peak demand.	%
Security of supply	The loss of load expectation arising from factors that cannot be mitigated by system operators.	Hours per year
Average lifecycle carbon per unit energy	The weighted average of lifecycle carbon per unit energy for all generation technologies contributing to the grid.	gCO_2/kWh
Aggregated land requirements	The total amount of area required to provide sufficient power to the grid.	km^2

Table 9 Comparison criteria for energy supply scenarios

5.3.1 2050 Baseline Generation Scenario

The 2050 scenario we have selected as the baseline for comparison is the "TECH100" which reaches Net Zero through more technology-based measures on a centralised energy system pathway referred to as "Clockwork". The power generation capacity and energy provided is outlined below in Figure 6 and Figure 7 respectively.

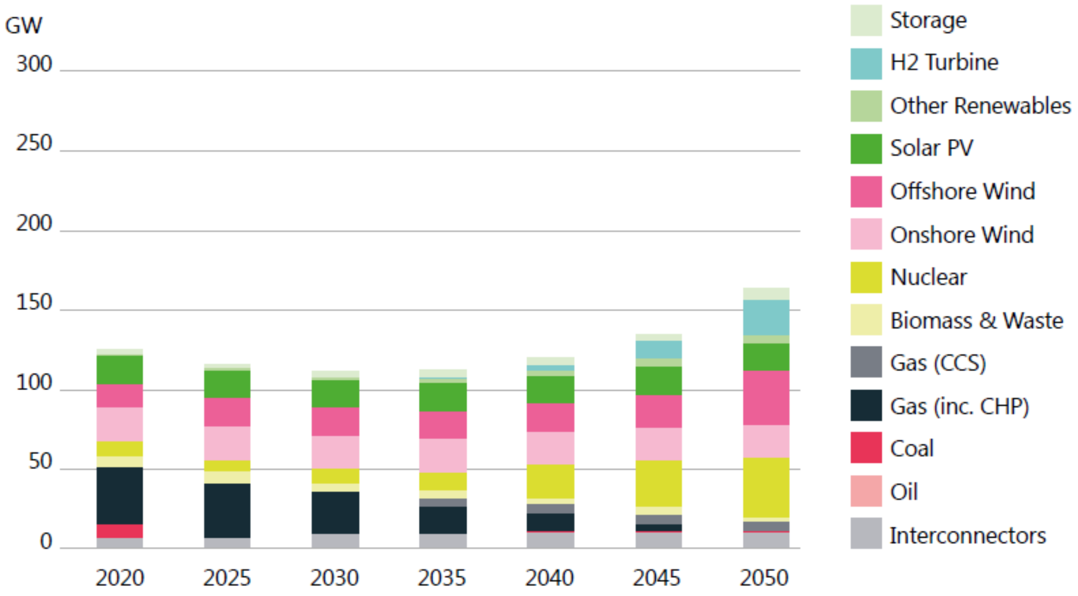

Figure 6: Baseline Generation Capacity (Energy Systems Catapult, 2020).

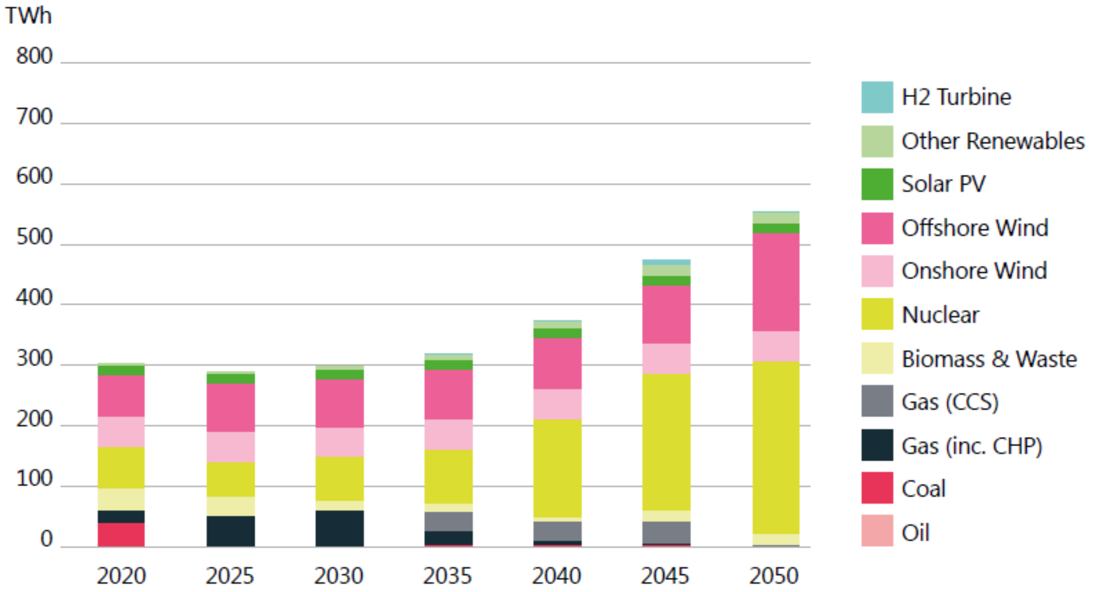

Figure 7: Baseline Annual Energy Generation Capacity (Energy Systems Catapult, 2020).

5.3.2 2050 Scenario Modified to Include SBSP

The scenario we have developed to include SBSP is based on the premise of replacing 10GW of nuclear capacity with 10GW of SBSP to provide similar baseload. This reduces the nuclear generation capacity from 37GW to 27GW. In turn it is assumed it will reduce the annual energy generation contribution by the same fraction, i.e. the 285TWh of nuclear generation in the baseline is reduced to 208TWh of nuclear generation and 77TWh of SBSP generation.

5.3.3 2050 Scenario comparison

Using the assessment criteria above and the comparison between nuclear and SBSP technology from Table 8 the difference in assessment criteria between the scenarios can be illustrated.

Technology Criterion	SBSP	Nuclear
LCOE	Amber	Green
Firm capacity	Green	Green
Intermittency	Green	Green
Predictability	Green	Green
Dispatchability	Green	Red
Grid operability	Red	Green
Lifecycle carbon per unit energy	Green	Green
Land power density	Amber	Green

Table 10: Extract of Comparison of SBSP against other potential Net Zero technologies

Scenario Criterion	Impact of SBSP	Difference between scenarios
Average Cost of Energy	Disadvantageous	SBSP may have a higher LCOE than nuclear energy, therefore there may be a cost increase.
Grid firm capacity	No significant change	SBSP appears to have a similar firm capacity to nuclear, therefore the overall grid firm capacity should be similar.
Security of supply	Advantageous	SBSP offers an alternative technology with different operating characteristics, without a requirement for externally supplied fuel. Therefore assuming the level of technical risk of a mature station is comparable, this should increase the security of supply.
Average lifecycle carbon per unit energy.	No significant change	SBSP and nuclear appear to have comparable lifecycle carbon per unit energy, therefore this should be similar.
Aggregated land requirements.	Disadvantageous	SBSP requires a larger area to operate per MW than nuclear stations, therefore there will be an increased land requirement.

Table 11: Difference between scenarios

5.4 SUMMARY

As highlighted previously, there are a large range of potential scenarios and pathways to reach them over the next 30 years. The comparison that has been performed here is based on the amount of nuclear plant falling short of what is required to achieve Net Zero.

In such an instance SBSP may lead to increases in the land requirements and cost of energy, but would increase the security of supply.

It is worth noting that:

- The work performed by the Energy Systems Catapult (Energy Systems Catapult, 2020) highlights that all of the nuclear, biomass, renewables and CCS possibilities available need to be realised, as well as the realisation of some speculative measures. If any one area is not fully utilised, the UK will not meet Net Zero.
- This scenario is based on aspirations for other technologies to deliver Net Zero falling short. Therefore although there are some disadvantages to using SBSP, if it was not used, then the UK would not meet Net Zero.
- As such, considering SBSP as part of an “energy portfolio” at this time decreases the overall “portfolio risk” of failing to meet Net Zero.
- Current values for LCOE of SBSP are immature, and technology costs are changing. They could increase, as well as decrease, depending on the results of further study.
- It may be feasible to reduce land impacts by deploying rectennas offshore. This is a speculative solution and its feasibility, cost and environmental impact have not been considered.

6. TECHNOLOGY ROADMAP

6.1 OVERVIEW

The UK and international roadmaps are presented in Annex C. They represent the technology development steps required at subsystem level to provide a viable pathway to commercial SBSP providing a significant contribution to the UK’s Net Zero 2050 ambition.

Due to the novelty of SBSP there is significant uncertainty and risk in its development, this risk arises from the following factors:

- The enormous scale of the proposed 2GW satellite in comparison to any space or terrestrial construction;
- The SBSP system concepts are themselves relatively immature;
- The economics depend heavily upon being able to engineer the satellite to a very low mass, yet the system requirements (which drive the mass) are poorly defined.

To address these risks a number of whole system demonstration steps are defined, each one advancing the overall TRL of SBSP by constructing a whole system at increasing scale in an environment closer to its final orbit. At each demonstration the aim is to:

- Better understand the system performance in the space environment, and how it will scale to the full size;
- Address known technical risks, and test the risk mitigation strategies;
- Provide data to inform the system design and validate computer models, to give confidence that the full size system will perform as expected;
- Develop the necessary enabling technologies and grow industrial capacity;
- Give progressive confidence for commercial investors to fund the technology.

It is important to note that, due to the scaling effects of microwave power transmission, the useable power from small scale SBSP is unlikely to be commercially viable. The stages before the large pilot demonstration are therefore for demonstration only. The demonstration stages selected for this roadmap reflect the consensus and uncertainty shown during the roadmapping workshop conducted with industry specialists.

The technology developments required for each demonstration feed in to these stages on the roadmap, showing the required level of development of the component sub systems. In most cases the whole system TRL reflect the TRL of the demonstration, however there are instances in the enabling systems where a more advanced state is required.

6.2 ROADMAPPING ASSUMPTIONS

The following assumptions were made to develop the roadmaps:

- Technological feasibility and engineering development time are the only constraints on technology development (i.e. not political, legal, social, financial or environment factors).
- Robotic assembly (whether tele-operated, automated or autonomous) will be required for in-space assembly.
- It is not expected that humans will have to work near the satellite.

- The UK can own an engineering capability without it having to be physically located in the UK (i.e. assets owned overseas).
- The grid is able to receive the power generated.
- While there have been proposals considering a wide range of construction/assembly orbits with alternative costs, this roadmap assumes assembly will be done in the final orbit location.
- The SBSP system in the roadmap has characteristics similar to Constant Aperture Solid State Integrated Orbital Phased Array (CASSIOPeiA).

6.3 COMPARISON OF UK AND INTERNATIONAL ROADMAPS

The international roadmap has the same system integration level milestones as the UK, as there have been no whole systems trials conducted, either internationally or within the UK.

The roadmaps do differ at subsystem level where international technology development is more advanced than the UK, leading to higher TRLs. In these subsystems there is less development required before the technology can be incorporated into the system level trials. The key differences in these levels of development are:

- **Space Lift:** The largest difference in TRLs and resulting pathway is due to the UK having very limited launch capability compared with both the required capacity for SBSP and the international capability. For the UK to develop SBSP entirely unaided by foreign nations a sovereign space lift programme would need to be developed. One of the options for such a UK space lift capability is the Synergetic Air Breathing Rocket Engine (SABRE) powered spaceplane proposed by Reaction Engines. Equatorial orbits are not accessible from the UK without significant penalty, however the UK would have access to the European Space Agency site in French Guyana.
- **Convert:** We have not found evidence that the UK has not pursued HCPV technology development, which can only be used effectively in space. Due to the location of the majority of UK land mass in the northern latitudes there is no reason for terrestrial HCPV to be deployed which is only efficient over a small incident angle. Even in terrestrial locations with high solar insolation, HCPV is not as economic as other PV technologies as the small incident angle means they require active tracking mechanisms to follow the Sun, ultimately leading to poorer economics compared to traditional panels.
- **Transmit** and **Receive:** Both of these subsystems, that together comprise the power beaming technology, have little testing within the UK comparatively to international trials. Thales Alenia Space and Airbus are leading companies in the UK for this technology. Establishing the viability of this technology is critical to the success of SBSP.
- **Satellite Maintenance** and **In-Orbit Assembly:** These technologies have similar development pathways as identified in Section 6.5. The UK's lack of experience in space construction is evident in the TRL discrepancy. However the UK is involved in current space robotics programmes (PERASPERA) and is growing in its automation and autonomy capability across industries. This technology could see wider benefits beyond SBSP as space industries develop for the UK and internationally.

The UK would either need to devote more resources to accelerate the development of these technologies to maintain pace with the international SBSP industry, or, partner with nations and organisations that have already developed the expertise. Both options would provide a route to SBSP by 2050, and it is likely a combination of both would be required. The optimum balance between these approaches is outside the scope of this report and would involve a number of Political, Economic, Social, Technological, Legal and Environmental (PESTLE) considerations.

Given the technological development required and the engineering barriers comparison between UK and international capability, current subsystems where the UK is well placed to maintain its lead, or catch-up include:

- Orbital robotics
- Satellite decommissioning
- Electric thrusters
- Control system
- Communication
- Large lightweight satellite structures
- Wireless power transmission
- Thermal management
- Terrestrial electrical machinery

6.4 ROADMAP ASSESSMENT

The roadmaps show that significant development is required across multiple key technologies both for the UK and internationally. As discussed in Section 6.3 there are aspects where UK development would require significantly more effort than international counterparts.

The subsystem and whole system demonstrator stages will be key to building confidence in the technology and de-risking investment. Crucially there are subsystems that will need to be more mature than the whole system to allow these demonstrations. This includes In-Orbit Assembly and Decommissioning. The assembly and decommissioning methods used at each demonstration must be reliable prior to the assembly of the demonstrator to reduce the risk during assembly and to comply with decommissioning legislation. This requirement is exacerbated by the relatively low TRL of these technologies which will require significant development to reach the timescales shown on the roadmap.

Both roadmaps represent an ambitious pathway to SBSP as a contributor to Net Zero. While the pathways are technically feasible they require investment representing, in some cases, significant increases on current levels to mature technologies within the specified timeframe. Development of launch capacity and satellite manufacture are currently driven by external factors that provide the demand for these services. This adds a significant amount of uncertainty to the roadmap but is vital to the development of SBSP.

The roadmaps illustrate that whilst some of the technologies are unique to SBSP others will also be used by other applications. In those cases where a technology is used in other application it may not be necessary to rely on a SBSP focused programme to develop the technology as funding will also come from elsewhere. The alternative applications may provide the commercial impetus to mature and refine the technology. This can have a significant impact on both the pace of development of those technologies as well as the level of capability that will be available to the SBSP programme. These parallel developments can have an impact not just on the development costs but also, through the economies of scale and reliability improvements, the capital and operating costs of SBSP.

The relative cost of the subsystems, and their contribution to LCOE as currently anticipated, will be reported in Phase 2. This will highlight which subsystems are either the most costly or the least efficient. Developing these subsystems will lead to a greater improvement to the LCOE. Additionally, any subsystems that contribute significant mass to the satellite and have opportunities for mass savings can potentially have a significant influence on launch cost, which is a key driver of LCOE.

The roadmaps showcase a pathway to SBSP by 2050. They represent the breadth and, for some technologies, depth of development still required to mature SBSP sufficiently to make a significant contribution to Net Zero. With sufficient resources, these development pathways are considered feasible for the UK and internationally based on the literature and understanding gathered from industry experts.

6.5 KEY POINTS FROM CONTRIBUTORS

Key comments from the workshops are presented here.

6.5.1 Satellite Collect

Mirror technology can be developed independently of other systems prior to integration with the pilot satellite system on the ground. Large mirrors can also be trialled independently in space as they are matured further, using existing space installations to secure them. As large mirrors reach the 100s of meters to km scale they are likely to need their own independent structures to support them in space, therefore requiring a link to the "Lightweight Structures" technology. At this point they would also need positioning systems in order to control their position in space, therefore they would also need control and communication systems. As such, as the mirror grows in size, it seems most efficient to include them as part of larger whole system trials.

6.5.2 Satellite Convert

HCPV technology can be developed simultaneously to other technology and whole system development with improvements in panel efficiency aiding the overall system efficiency. Intermediate whole system trials are not reliant on HCPV to demonstrate the concept and can instead use lower efficiency panels. The panels can be trialled on the ground in laboratory environments to recreate the features of space; expected temperature, radiation, vacuum and unfiltered sunlight. Panels with sufficient robustness and performance will need to be available prior to the large pilot scale demonstration.

6.5.3 Satellite Transmit

Microwave power transmission can be matured as an individual technology ahead of implementation into the whole system at pilot. The levels include, terrestrial long distance trials such as those conducted in Hawaii (Kaya & Mankins, 2010) at higher level of efficiency transmitting useful levels of power and retro directive beam accuracy. Continuing to improve efficiency and accuracy at distances appropriate to the preceding level of system will likely be required before each system demonstration. This could be done so using a reverse transmission, beam power into space, to avoid producing power in space.

6.5.4 Satellite Structure

The structure development is integral for any large scale whole system trials. The technology can be developed terrestrially to improve modelling capability, material performance and construction techniques. The system links strongly to the assembly method and concept of operation due to the uncertainty around building large structures in space. The structures technology must be sufficiently developed at all stages of the whole system demonstration as it cannot be substituted for a lower grade technology while demonstrating the system capability.

6.5.5 Satellite Station Keeping

This technology is currently in development and should continue its current rate of development however it is unlikely to be on the critical path to whole system demonstration until large pilot demonstration or later. While some form of station keeping is required the platform efficiency and longevity will not need to be fully materialised until this stage. Therefore more traditional propellant thrusts could be substituted (if it was beneficial or more cost effective) without sacrificing the whole system demonstration. At full scale, the system will remain in orbit for decades and so avoiding or reducing the propellant resupply by using electric thrusters will produce significant benefits.

6.5.6 Satellite Control

Developing the control technology required for large satellites in space will be essential at each stage of the whole system demonstration, in particular when the size exceeds any current satellite.

6.5.7 Satellite Communication

Currently communication technology is likely sufficient for early whole system demonstrations. However when the whole system become part of our critical national infrastructure communication will need to be robust and integrated with other systems such as power station control. Hence further development is required ahead of the whole system pilot system trials demonstration.

6.5.8 Ground Receive

Similar to Satellite Transmit technology, the rectenna efficiency must be demonstrated ahead of integration into the whole system. The technology can be matured as an individual technology ahead of implementation into the whole system at pilot scale. The levels include terrestrial long distance trials such as those conducted in Hawaii (Kaya & Mankins, 2010) at higher level of efficiency transmitting usable levels of power. Continuing to improve efficiency at distances appropriate to the preceding level of system will likely be required before each system demonstration. Reverse transmission could be used, beaming power into space. Deploying a small area of rectenna and pilot beam technology into orbit would allow power density and accuracy tests to be conducted at a range of distances.

6.5.9 Ground Convert

This technology is similar to that used in terrestrial solar. There is limited development required besides component selection for deployment at whole system demonstrations.

6.5.10 Ground Distribute

This technology is similar to that used in terrestrial solar. There is limited development required besides component selection for deployment at whole system demonstrations.

6.5.11 Ground Structure

This technology is similar to that used in terrestrial solar. There is limited development required besides component selection for deployment at whole system demonstrations.

6.5.12 Ground Grid Connection

This technology is similar to that used in terrestrial solar. There is limited development required besides component selection for deployment at whole system demonstrations.

6.5.13 Ground Control System

The large size of the satellites proposed mean that additional consideration for control methods will need to be considered. Experience controlling large satellites will likely be established through a combination of computational modelling extending the currently capability and whole system demonstrations.

6.5.14 Ground Communication

The importance of a space based solar power satellite to the national energy mix will mean that existing satellite communication methods will need to be strengthened. This includes control of the retro directive pilot beam to ensure power is delivered in the right location as discussed under Satellite Receive. These communication methods can be developed and tested outside of the whole system demonstration programme and integrated ahead of the large pilot demonstration. Although where security is a concern ongoing development and implementation will be required.

6.5.15 Satellite Operation

Similar to Ground Communication, the importance of a space based solar power satellite to the national energy mix will mean that existing satellite operation methods will need to be strengthened. These methods can be developed and tested outside of the whole system demonstration programme and integrated ahead of the large pilot demonstration. Although where security is a concern ongoing development and implementation will be required.

6.5.16 Satellite Maintenance

When conducting initial demonstrations at pilot system trials it is unlikely significant maintenance will be conducted, instead the satellite will be allowed to gracefully degrade. Doing so gather data on degradation rates. At large pilot demonstration scale and beyond the technology is closely linked to in-orbit assembly, it is assumed the maintenance will consist of replacing modules within the system that are faulty. As a result, the same robotics development required for assembly will be deployed during maintenance. Significant advancements in this technology are required ahead of deployment at large pilot demonstration whole system level. For the first pilot system trials it is assumed that the smaller satellite will be assembled with significant human interaction, either directly by:

- Humans;
- Humans in space operating robots;
- Tele robotics from earth, or;
- A combination of the above.

6.5.17 Power Station Operation

There are additional challenges of integrating with satellite operation and control to ensure predictable power delivery. This will require collaboration between energy supplier, national grid and the satellite operator if they are all separate entities. Otherwise the operation is similar to terrestrial solar technology.

6.5.18 Satellite Manufacture

Significant development of satellite manufacture is required in order achieve the scale necessary to produce a full scale SBSP system. This will require a ramp up for industry with some certainty over future demand to provide the investment in mass production which will likely be specific to a SBSP design. Achieving this represents a major challenge.

6.5.19 Space Lift

The development of adequate Space Lift capability will be dependent on whether the UK develops and uses its own sovereign space lift capacity or is willing to purchase capacity with international suppliers. The Reaction Engines Synergetic Air Breathing Rocket Engine (SABRE) powered spaceplane concept is potentially a low cost reusable UK space launch technology, however it is immature. The SABRE which would power the spaceplane underwent trials of one of its key components in 2019 (Reaction Engines, 2020). A UK sovereign space lift capability would require significant and rapid development of a space programme from very low TRL. Using international capability presents potential energy security threats but enables a far less onerous development pathway.

6.5.20 In-Orbit Assembly

Similar to satellite maintenance, with increasing size it is likely there will be a shift from human assembly to robotic assembly. To assemble a full scale 2GW whole system satellite in space within the Net Zero 2050 timescale will require significant development of large scale robotics with some capacity to act with autonomy and recognise when human intervention is required. This technology requires significant development with increasing levels of sophistication required at each whole system demonstration.

6.5.21 Satellite Decommissioning

Requirements to have demonstrated the decommissioning technology ahead of satellite deployment mean that decommissioning must be considered at design stage. This technology requires significant development ahead of the first whole system pilot to prove it can be decommissioned. As the satellite size increases more complex decommissioning methods may be required. These will need to be demonstrated, potentially on the preceding whole system demonstrator. Therefore, the satellite decommissioning technology must not only catch up its development to other technology but must also remain ahead of the whole system TRL.

6.5.22 Rectenna Manufacture

The technology will benefit from similar technology, such as 5G, increasingly being manufactured at scale. However, changes in the mass production methods may be required to suit differences in the technology. This will require development and sufficient certainty in demand for industry to increase production volumes to the levels required for the full scale rectenna.

6.5.23 Power Facility Manufacture

This technology is similar to that used in terrestrial solar. There is limited development required besides component selection for deployment at whole system demonstrations.

6.5.24 Control Station Manufacture

This technology is similar to that used in existing space missions. The UK may require more advanced control station systems than currently exist however these are likely to be available internationally.

6.5.25 Ground Station Manufacture

This technology is similar to that used in terrestrial solar. There is limited development required besides component selection for deployment at whole system demonstrations.

7. SUMMARY AND RECOMMENDATIONS

The aim of this project is to assess the evidence base to justify the value of further investment into understanding SBSP as a contributor to the UK's 2050 Net Zero target. In particular the focus is to understand whether it is feasible, from an engineering perspective, for SBSP to support the delivery of Net Zero. In answering this we have addressed what is required to deliver this SBSP capability.

7.1 FEASIBILITY AND MAJOR ENGINEERING BARRIERS FOR THE UK TO OVERCOME

The study has shown that, while there are significant challenges, the engineering development required to realise a 10GW SBSP capability in 2050 is feasible, and that SBSP could contribute to the UK energy system and support Net Zero. The study has reviewed:

- The engineering barriers to be overcome
- The technological development required, and
- The roadmaps that are required in order to deliver sufficient SBSP capability by 2050.

The key engineering barriers to achieving SBSP in order to support Net Zero in 2050 are:

- Technology maturation across all subsystems. The most immature subsystem is for decommissioning the satellite. Other subsystems requiring significant development are the energy subsystems on the satellite, structural and control subsystems, in-orbit assembly and maintenance robotics.
- Sufficient production facilities to manufacture the satellites.
- Sufficient launch capability to deliver the satellites to their operational orbits.

Additionally, a number of whole system engineering barriers have been identified:

- Sufficient land area to deploy the rectennas.
- System security and debris damage withstand.
- There is a potential risk of material shortages for the manufacture of the solar photovoltaic technology currently being pursued.

7.2 THE UK'S ROLE WITHIN SBSP

The study has developed roadmaps to identify the activities required in order to deliver sufficient SBSP capability by 2050. These roadmaps shows that significant development is required across multiple key technologies both for the UK and internationally. Both roadmaps represent an ambitious pathway to SBSP as a contributor to Net Zero. While the pathways are technically feasible they require investment representing. In some cases, significant increases on current levels to mature technologies within the specified timeframe.

Given the technological development required and the engineering barriers comparison between UK and international capability, current subsystems where the UK is well placed to maintain its lead, or catch-up include:

- Orbital robotics
- Large lightweight satellite structures

- Satellite decommissioning
- Electric thrusters
- Control system
- Communication
- Wireless power transmission
- Thermal management
- Terrestrial electrical machinery

It may also be feasible to consider the UK as a base for the test sites required to advance SBSP.

There are also a number of technology elements where the UK development would require significantly more effort than international counterparts. Currently the UK has the greatest challenge overcoming barriers to deliver sufficient space launch and sufficient manufacturing capacity.

7.3 RECOMMENDATIONS

The following recommendations are made:

- As SBSP appears feasible from an engineering perspective it is recommended that Phase 2 of this project is undertaken to better understand the cost and economic impact.
- Pending an acceptable outcome to the cost and economic assessment in Phase 2 it is recommended that the next steps after are initial assessments across societal impact, social acceptance, international and local legal implications, standards development and environmental impact.
- This study has been developed using a representative system architecture and target capability of five 2GW SBSP installations. It is recommended that a Front End Engineering Design study is performed to develop System Requirements, and develop and assess the architecture and design options, performance, risks and through-life costs to a greater degree of confidence.

8. ACRONYMS

BEIS	Department for Business, Energy and Industrial Strategy
CAPEX	Capital Expenditure
CASSIOPeiA	Constant Aperture Solid-State Integrated Orbital Phased Array
CCS	Carbon Capture and Storage
CNI	Critical National Infrastructure
ELSA	End-of-Life Service by Astroscale
EM	Electromagnetic
EMI	Electromagnetic Interference
EROSS	European Robotic Orbital Support Services
GEO	Geostationary Earth Orbit (or Geosynchronous Equatorial Orbit)
GTO	Geostationary Transfer Orbit
GW	Giga Watt
HCPV	High Concentration solar Photovoltaic
ISS	International Space Station
LCOE	Levelised Cost Of Energy
LEO	Low Earth Orbit
MEV	Mission Extension Vehicle
MODAR	Modular Spacecraft Assembly and Reconfiguration Demonstrator
MR-SPS	Multi-Rotary Solar Power Satellite
PESTLE	Political, Economic, Social, Technological, Legal and Environmental
PV	Photovoltaic
RF	Radio Frequency
SABRE	Synergetic Air Breathing Rocket Engine
SBSP	Space Based Solar Power
SME	Subject Matter Expert
SPS-ALPHA	Solar Power Satellite Via Arbitrarily Large Phased Array
TRL	Technology Readiness Levels

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ANNEX A - TECHNOLOGY READINESS LEVELS

A.1 TECHNOLOGY READINESS LEVELS

The Technology Readiness Levels (TRLs) used in this study are shown below in Table 12.

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.

Table 12: TRL definitions

ANNEX B - TECHNOLOGY FEASIBILITY ASSESSMENTS

B.1 TECHNOLOGY FEASIBILITY ASSESSMENT

This section runs through each of the major system elements from the whole system view and reviews their feasibility by looking at their TRL and barriers. All engineering barrier information is derived from the stakeholder workshops conducted (Frazer-Nash Consultancy, 2020).

B.1.1 SYSTEM ELEMENT: SATELLITE COLLECT

Critical enabling technology: Large (km scale) mirror in space

Description: Redirect incoming sunlight onto the "Convert" subsystem.

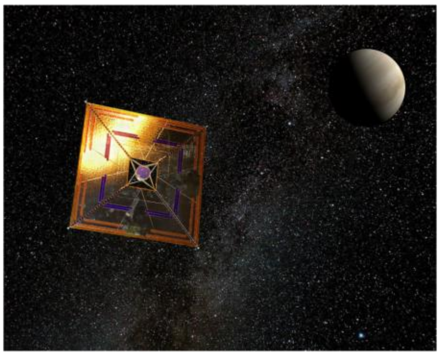

Figure 8 – Illustration of the JAXA IKAROS spacecraft [1].

UK TRL		3	UK TRL justification	No specific UK experiments have taken place, therefore UK TRL is informed by research in the international public domain.
UK major engineering barriers	▸	▸ Experience of manufacturing large reflective surfaces for use in space. ▸ Sufficient manufacturing capacity for large reflective surfaces in space. Current materials suggested for construction are not on the 2020 EU critical raw materials list (European Comission, 2020), therefore this is not a significant barrier.		

International TRL	5	International TRL justification	A 14m x 14m reflective sail was deployed on JAXA's Interplanetary Kite-craft Accelerated by Radiation Of the Sun (IKAROS) in 2010 and has operated in space (Japan Aerospace Exploration Authority, 2015). The reflector is unlikely to be representative of the final SBSP system design. The reflector itself is at TRL 5/6 but the structure and control to enable it to be the large surface require needs more development.
International major	▸ Manufacturing capacity for large reflective surfaces in space.		

engineering barriers	Current materials suggested for construction are not on the 2020 EU critical raw materials list (European Comission, 2020), therefore this is not a significant barrier.

Technically feasible	Yes	Feasibility justification	While technology requires development, the greatest barrier is likely to be the development of sufficient manufacturing capacity.
Difficulty	High	Difficulty justification	Increasing the scale of deployment of this technology represents a significant difficulty in its development.

B.1.2 SYSTEM ELEMENT: SATELLITE CONVERT

Critical enabling technology: High efficiency space PV and power electronics

Description: Convert sunlight into electrical energy in a suitable form to supply the "Transmit" subsystem. Includes any power conditioning required prior to transmission.

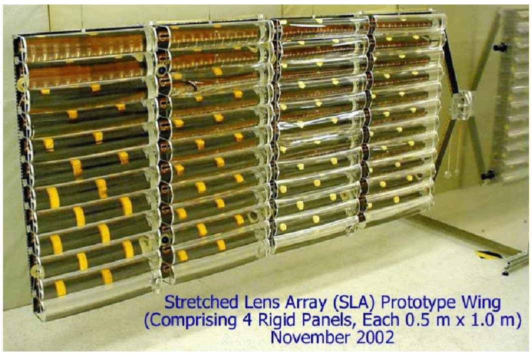

Figure 9 – Stretched Lens Array prototype [2].

UK TRL	3	UK TRL justification	No specific UK experiments have taken place, therefore UK TRL is informed by research in the international public domain.
UK major engineering barriers	Technology development of High-Concentration Photovoltaic (HCPV) is required to reduce mass and increase efficiency. This is hindered by the lack of terrestrial application, particularly in the UK. Sufficient manufacturing capacity for solar panels for space. Germanium, gallium, indium and other materials on the EU critical raw materials list may be required (European Comission, 2020). Triple junction perovskites may address this (Wang, 2020).		

International TRL	6	International TRL justification	The Stretched Lens Array for concentrating light has been tested in the laboratory (O'Neill, 2006). Dual-junction solar cells have been deployed on NASA's Deep Space 1 in space in 1998 as part of the Solar Concentrator Array with Refractive Linear Element (SCARLET) (NASA, 2019). Triple-junction cells have also been deployed in space with concentrator modules (Takamoto, 2014). In summary, concentration and high-efficiency PV has been demonstrated in space on working systems, but not as part of an SBSP prototype.
International major	Technology development of HCPV is required to reduce mass and increase efficiency.		

engineering barriers	- Germanium, gallium, indium and other materials on the EU critical raw materials list may be required (European Comission, 2020). Triple junction perovskites may address this (Wang, 2020).		
Technically feasible	Yes	Feasibility justification	While barriers exist with sufficient technology development they will likely be overcome to produce high efficiency solar panels for use in space.
Difficulty	Medium	Difficulty justification	Further development of HCPV is required to achieve the efficiencies required, this development is not likely to be driven by a terrestrial need.

B.1.3 SYSTEM ELEMENT: SATELLITE TRANSMIT

Critical enabling technology: Microwave power beam transmission at scale

Description: Converts electrical energy into Radio Frequency (RF) energy and beams it off of the satellite. Includes beam forming.

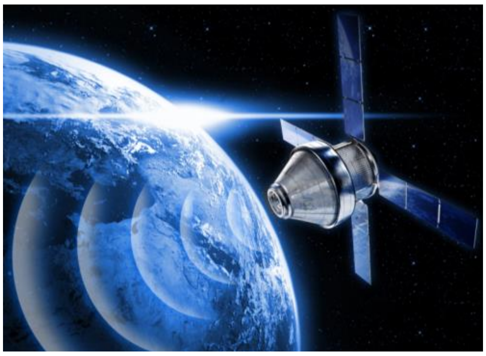

Figure 10 – Illustration of microwave power beam transmitting to earth [3].

UK TRL	3	UK TRL justification	No specific UK experiments have taken place, therefore UK TRL is informed by research in the international public domain. Closest UK example is the theoretical work on MicroLaunch which beamed microwaves to launch satellites (Bacon, 2015).
UK major engineering barriers	‣ Experience manufacturing large, efficient, power transfer antennas. ‣ Sufficient manufacturing capacity for antennas. ‣ Technology is inefficient at small scale so difficult to test unless done at large scale. ‣ Challenges producing a coherent beam on a flexible structure ‣ Materials such gallium may be required, which are on the EU critical raw materials list may be required (European Comission, 2020) ‣ Must be allocated frequency bands and agree at international level to avoid inference with extant systems.		

International TRL	4	International TRL justification	Mitsubishi Heavy Industries has demonstrated a transmission of 10kW over a distance of 500m using microwaves on the ground (Ackerman, 2015). This is small scale and not in a relevant environment (i.e. space).
International major engineering barriers	‣ Technology is inefficient at small scale so difficult to test, some testing has been conducted however further work is required to prove high efficiencies and accuracies necessary for space based solar power. ‣ Sufficient manufacturing capacity for antennas. ‣ Challenges producing a coherent beam on a flexible structure.		

	‣ Materials such gallium may be required, which are on the EU critical raw materials list may be required (European Comission, 2020). ‣ Must be allocated frequency bands and agree at international level to avoid inference with extant systems.

Technically feasible	Yes	Feasibility justification	Further work is needed to confirm that high efficiency and accuracy beam forming is possible over long distances. This represents the one of the most significant technology barriers to space based solar power.
Difficulty	Very High	Difficulty justification	This technology require significant further development in efficiency and accuracy with limited opportunity to test at the scale required.

B.1.4 SYSTEM ELEMENT: SATELLITE THERMAL MANAGEMENT

Critical enabling technology: Space power electronics cooling

Description: Maintain the temperature of the components to manage their performance and life

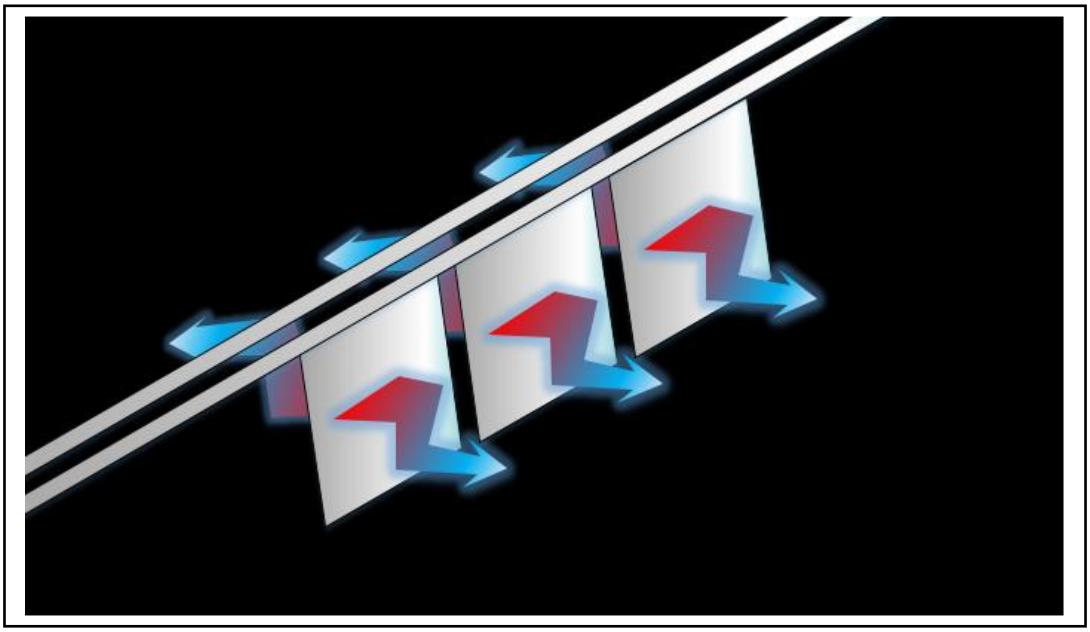

Figure 11 – Representation of radiating heat to space [4].

UK TRL	4	UK TRL justification	The UK's limited experience with building satellites through Surrey Satellites is sufficient to demonstrate that we are above TRL 3, however existing satellites have been low power and small scale them (Surrey Satellites, n.d.). According to participants in the TRL workshop there is a UK Catapult programme improving satellite cooling.
UK major engineering barriers	‣ Some designs claim to need active thermal management, some do not. This results in uncertain cooling technology requirements. ‣ Further work in passive cooling in space is required including an understanding of thermal loads and ability to dissipate heat in space, through enhanced modelling and testing.		

International TRL	5	International TRL justification	The International Space Station has multiple cooling systems onboard with radiators to emit excess heat into space (Tate, 2013). This represents integration of a system with reasonably similar supporting elements, however the system used on SBSP may need to implement a different approach due to the scale involved.

International major engineering barriers	- Some designs claim to need active thermal management, some do not. This results in uncertain cooling technology requirements. - Further work in passive cooling in space is required including an understanding of thermal loads and ability to dissipate heat in space, through enhanced modelling and testing.

Technically feasible	Yes	Feasibility justification	The technology advancements required are achievable with sufficient finance given current levels of technology and understanding. Some existing large satellite technology and lessons learnt will be applicable.
Difficulty	Medium	Difficulty justification	Further work is required however it appears to be similar to other technologies and is not considered to be difficult to scale.

B.1.5 SYSTEM ELEMENT: SATELLITE STRUCTURE

Critical enabling technology: Lightweight large scale structures in space

Description: Hold the components of the satellite in position relative to one another

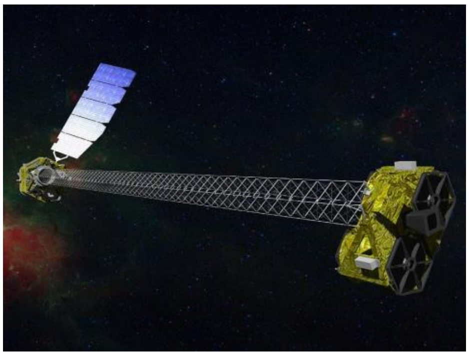

Figure 12 – Illustration of a large scale satellite structure [5].

UK TRL	3	UK TRL justification	Oxford Space Systems are performing theoretical research into lightweight deployable structures in space, but at a much smaller scale (Oxford Space Systems, 2020). There are many large terrestrial structures in the UK, which provides some analogy, but with significantly different mass. Additionally we have experience of designing satellite structures, but much smaller and likely a different design approach.
UK major engineering barriers	‣ New materials may need to be further developed and understood to be applied in space ‣ Advances in designing and modelling large scale structures in space are required. ‣ Limited experience launching and assembling large scale structures in space. ‣ Challenges of modular assembly for robotics while retaining structural stiffness ‣ Sufficient manufacturing capacity for large structures in space.			

International TRL	3	International TRL justification	The use of advanced materials in space for large scale, low-mass and high-strength structures is at an analytical stage (Mankins, 2012).
International major engineering barriers	‣ New materials may need to be further developed and understood to be applied in space ‣ Advances in designing and modelling large scale structures in space are required. ‣ Limited experience launching and assembling large scale structures in space.			

	▸ Challenges of modular assembly for robotics while retaining structural stiffness ▸ Sufficient manufacturing capacity for large structures in space.

Technically feasible	Yes	Feasibility justification	Material advances are required as well as further development of assembly and construction methods in space to realise large space structures. Given current research and advancements this is deemed to be feasible.
Difficulty	Very High	Difficulty justification	Achieving structure of the magnitude stated will require significant development across a number of areas including modelling and materials. The scale required significantly increases the difficulty with limited ability to test at scale.

B.1.6 SYSTEM ELEMENT: SATELLITE STATION KEEPING

Critical enabling technology: Electric thrusters

Description: Provide the force required to keep the satellite in its required position

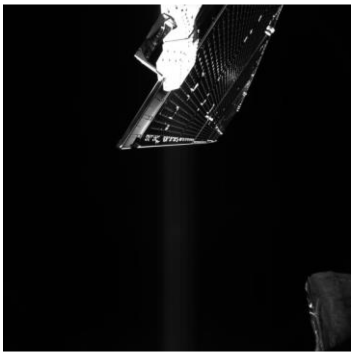

Figure 13 – Snapshot of the rotating solar arrays of the BepiColombo Mercury Transfer Module, used to provide propulsion [6].

UK TRL	6	UK TRL justification	QinetiQ have developed and produced a solar electric propulsion system used in the 2018 BepiColombo mission to Mercury (QinetiQ, 2018). Therefore this technology has been demonstrated in space, albeit as part of another system.
UK major engineering barriers	‣ The main barrier is around scalability and refinement of existing technology to be applicable to a large lightweight structure. Encompassing the use of electric thrusters and mechanical damping required to provide station keeping while minimising structural mass ‣ Additionally the whole system issues must be considered, e.g. any expelled propellant does not cloud mirrors or solar panels.		

International TRL	6	International TRL justification	The electric propulsion demonstrated by QinetiQ is representative of international technology development – i.e. tested in space on operational system, but not as part of SBSP.
International major engineering barriers	‣ The main barrier is around scalability and refinement of existing technology to be applicable to a large lightweight structure. Encompassing the use of electric thrusters and mechanical damping required to provide station keeping while minimising structural mass ‣ Additionally the whole system issues must be considered, e.g. any expelled propellant does not cloud mirrors or solar panels.		

Technically feasible	Yes	Feasibility justification	The appropriate technology is available however it must be refined to be effective on a large structure.

Difficulty	High	Difficulty justification	The increase in scale compared to other space structures means the difficulty is high, additional challenges will likely arise that are not present on current space structures.

B.1.7 SYSTEM ELEMENT: SATELLITE CONTROL SYSTEM

Critical enabling technology: Integrated control system of sensors, processing and control logic

Description: Sensors and logic to control and monitor all aspects of the satellite, notably the power being produced, the position of the satellite and the targeting of the transmission. Power production, supervision and safety control

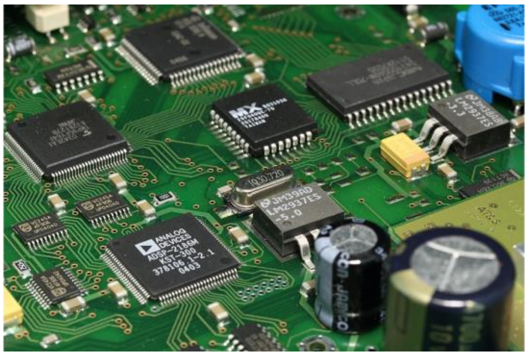

Figure 14 – Circuit board representing the satellite control system [7].

UK TRL	5	UK TRL justification	Surrey Satellites develop small scale satellites and operate them (Surrey Satellites, n.d.). The control systems are therefore used in space, however they are much less complex than what is foreseen for SBSP to manage the structural response, power and security of the system.
UK major engineering barriers	‣ New control systems for large satellites with significant area for photon pressure will need to be developed. This will require enhanced modelling and testing of the behaviour of very large structures in space ‣ Development of new sensors to aid control systems and manage response to debris is likely to be required. ‣ Methods for controlling the antenna beam will need to be developed that are resilient to maintain the security of the power supplied to prevent interruption. ‣ The control system is likely to be far more complex than for existing satellites. The architecture of the control system, particularly whether it is centralised or decentralised, is a key question.		

International TRL	5	International TRL justification	Many satellites and space stations have been developed and operated in space (for example Deep Space 1 (NASA, 2019)), however they are much less complex than what is foreseen for SBSP to manage the structural response, power and security of the system.
International major	‣ New control systems for large satellites with significant area for photon pressure will need to be developed. This will require enhanced		

engineering barriers	modelling and testing of the behaviour of very large structures in space - Development of new sensors to aid control systems and manage response to debris is likely to be required. - Methods for controlling the antenna beam will need to be developed that are resilient to maintain the security of the power supplied to prevent interruption. - The control system is likely to be far more complex than for existing satellites. The architecture of the control system, particularly whether it is centralised or decentralised, is a key question.

Technically feasible	Yes	Feasibility justification	Advancements in control technology are required but deemed achievable.
Difficulty	Medium	Difficulty justification	Similar technology is in use for current satellites. To adapt to the much larger scale developments must be made however these are likely to be iterative improvements on current control systems.

B.1.8 SYSTEM ELEMENT: SATELLITE COMMUNICATIONS

Critical enabling technology: Space telemetry link

Description: Transmit data to the ground station and receive data from the ground station for the purposes of control and system monitoring

Figure 15 – Illustration of radio transmitter in space [8].

UK TRL	5	UK TRL justification	Surrey Satellites develop small scale satellites and operate them (Surrey Satellites, n.d.). The communication systems are therefore used in space, however they are likely to have lower bandwidth and less secure than that required to operate complex critical national infrastructure.
UK major engineering barriers	‣ More robust communication required as SBSP will be Critical National Infrastructure. ‣ Within-satellite communication methods might use approaches such as Wi-Fi. This must be contained so as not to interfere with other satellites. ‣ The communication system is likely to need to have greater bandwidth than existing satellite systems. The architecture of the communications system, particularly whether it is centralised or decentralised, is a key question.		

International TRL	6	International TRL justification	Many satellites and space stations have been developed and operated in space (for example Deep Space 1 (NASA, 2019)). The communication systems are therefore used in space, and given the complexity of some satellites and the needs of manned spaceflight they may have similar bandwidth and security to that required to operate complex critical national infrastructure.
International major engineering barriers	‣ More robust communication required as SBSP will be Critical National Infrastructure.		

	- Within-satellite communication methods might use approaches such as Wi-Fi. This must be contained so as not to interfere with other satellites. - The communication system is likely to need to have greater bandwidth than existing satellite systems. The architecture of the communications system, particularly whether it is centralised or decentralised, is a key question.

Technically feasible	Yes	Feasibility justification	Protocols must be established but existing communication technology is likely highly transferable.
Difficulty	Low	Difficulty justification	Similar technology for communicating with current satellites exists. Changes will be required however these will be largely unaffected by scale.

B.1.9 SYSTEM ELEMENT: GROUND RECEIVE

Critical enabling technology: Rectenna for power conversion

Description: Collect RF energy transmitted by the satellite and convert it into electrical energy

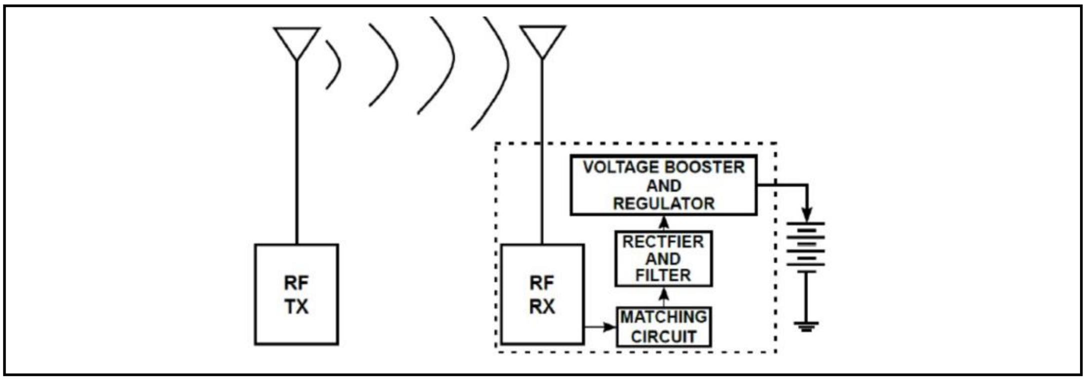

Figure 16 – Diagram of a rectenna used to harvest RF energy [9].

UK TRL	3	UK TRL justification	No specific UK experiments have taken place, therefore UK TRL is informed by research in the international public domain.
UK major engineering barriers	‣ Limited understanding and experience of large-scale rectenna technology ‣ Inability to test over the required distances on Earth. ‣ Due to diffraction physics there is a link between the size of the satellite antenna and the size of the rectenna on Earth. To minimise the size of the satellite the rectenna area required on Earth is large. A smaller rectenna could be used, but only a fraction of the power beamed would be captured, however this would still demonstrate the physics.		

International TRL	5	International TRL justification	Others have claimed TRLs of between 4 and 6 based on the form of the rectenna (Mankins, 2011). Mitsubishi Heavy Industries has demonstrated a transmission of 10kW over a distance of 500m using microwaves on the ground (Ackerman, 2015). This is small scale but it is in a representative environment (i.e. on the ground).
International major engineering barriers	‣ Inability to test over the required distances on earth ‣ Due to diffraction physics there is a link between the size of the satellite antenna and the size of the rectenna on Earth. To minimise the size of the satellite the rectenna area required on Earth is large. A smaller rectenna could be used, but only a fraction of the power beamed would be captured, however this would still demonstrate the physics.		

Technically feasible	Yes	Feasibility justification	The technology has shown to be theoretically possible and trials have demonstrated this to some extent.
Difficulty	High	Difficulty justification	Ensuring the efficiency of the rectenna at the scale needed is achieve significant further work is required.

B.1.10 SYSTEM ELEMENT: GROUND CONVERT

Critical enabling technology: Electrical inverter

Description: Convert electrical energy into a form suitable for input to the grid. Includes grid operability measures, i.e. power conditioning, reactive power management

Figure 17 – GE Electric Inverter [10].

UK TRL	7	UK TRL justification	Solar PV stations have very similar systems for inverting, power conditioning and management of reactive power as those foreseen for SBSP. GE are an example of a company that operate in the UK and produce electrical machinery for solar farms (General Electric, n.d.) (General Electric, n.d.).
UK major engineering barriers	No significant engineering barriers foreseen.		

International TRL	7	International TRL justification	Solar PV stations have very similar systems for inverting, power conditioning and management of reactive power as those foreseen for SBSP. The largest PV stations in commercial use have a capacity in excess of 2GW (Ranjan, 2019)
International major engineering barriers	No significant engineering barriers foreseen.		

Technically feasible	Yes	Feasibility justification	Technology easily transferred from similar applications.
Difficulty	Low	Difficulty justification	This will largely require transfer of technology for similar industries such as terrestrial solar with adaptations to meet differing requirements.

B.1.11 SYSTEM ELEMENT: GROUND DISTRIBUTE

Critical enabling technology: Transformers and cable

Description: Gather electrical energy from across the site and transmit it to the grid connection. Includes voltage step-up

Figure 18 – Example of industrial transformers [11].

UK TRL	7	UK TRL justification	Solar PV stations have very similar systems for inverting, power conditioning and management of reactive power as those foreseen for SBSP. Companies such as R Baker produce transformers up to 250kW (R Baker (Electrical) Ltd, 2018).
UK major engineering barriers	No significant engineering barriers foreseen.		

International TRL	7	International TRL justification	Solar PV stations have very similar systems for inverting, power conditioning and management of reactive power as those foreseen for SBSP. The largest PV stations in commercial use have a capacity in excess of 2GW (Ranjan, 2019).
International major engineering barriers	No significant engineering barriers foreseen.		

Technically feasible	Yes	Feasibility justification	Technology easily transferred from similar applications.
Difficulty	Very Low	Difficulty justification	This will largely require transfer of technology for similar industries such as terrestrial solar with adaptations to meet differing requirements.

B.1.12 SYSTEM ELEMENT: GROUND STRUCTURE

Critical enabling technology: Terrestrial structures

Description: Hold the components of the ground station in position relative to one another

Figure 19 – Aerial image of a solar farm showing typical ground structures [12].

UK TRL	7	UK TRL justification	Structures are mature for satellite Communications, Control Systems and Operation (see relevant subsystems). Although the UK has lower TRL of "Receive" technology, the structures are likely comparable to existing renewables technology. These structures have not yet been built for an actual SBSP system at scale.
UK major engineering barriers	No significant engineering barriers foreseen.		

International TRL	7	International TRL justification	Structures are mature for satellite Communications, Control Systems, Operation and Receiving wireless power (see relevant subsystems). These structures have not yet been built for an actual SBSP system at scale.
International major engineering barriers	No significant engineering barriers foreseen.		

Technically feasible	Yes	Feasibility justification	While the exact requirement is unknown the challenge is not deemed to be disproportionate to other engineering structures already in existence.
Difficulty	Low	Difficulty justification	This will largely require transfer of technology for similar industries such as terrestrial solar with adaptations to meet differing requirements. While the scale is significant the technical challenges are not deemed to be substantial.

B.1.13 SYSTEM ELEMENT: GROUND GRID CONNECTION

Critical enabling technology: Grid interface monitoring and switch

Description: Provide a controllable connection between the ground station output and the distribution/transmission network.

Figure 20 – Example of connection to the grid [13].

UK TRL	7	UK TRL justification	Solar PV stations have very similar grid connections as those foreseen for SBSP. Siemens are an example of a company that operate in the UK and transmission switchgear (Siemens Energy, 2020) (Siemens, 2020).
UK major engineering barriers	No significant engineering barriers foreseen.		

International TRL	7	International TRL justification	Solar PV stations have very similar grid connections as those foreseen for SBSP. The largest PV stations in commercial use have a capacity in excess of 2GW (Ranjan, 2019).
International major engineering barriers	No significant engineering barriers foreseen.		

Technically feasible	Yes	Feasibility justification	Grid connections for analogous electricity generation technology already exist.
Difficulty	Very Low	Difficulty justification	This will require transfer of technology for similar industries such as terrestrial solar.

B.1.14 SYSTEM ELEMENT: GROUND CONTROL SYSTEM

Critical enabling technology: Integrated control system of sensors, processing and control logic

Description: Sensors and logic to control all aspects of the satellite, notably the power being produced, the position of the satellite and the targeting of the transmission. Effectors, sensors and logic to control the connection with the grid in terms of the power extracted/supplied

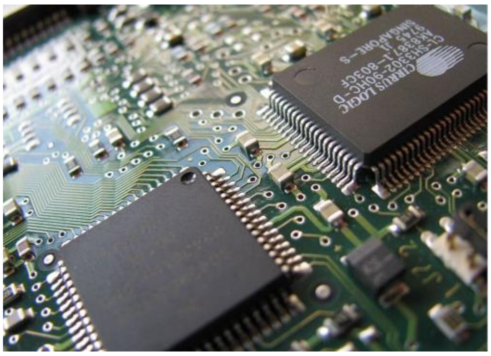

Figure 21 – Circuit board illustrative of an integrated control system [14].

UK TRL	5	UK TRL justification	Surrey Satellites develop small scale satellites and operate them (Surrey Satellites, n.d.). The control systems are therefore used on the ground to communicate with space, however they are much less complex than what is foreseen for SBSP to manage the structural response, power and security of the system.
UK major engineering barriers	▸ Limited experience in the control of large, complex satellites that are Critical National Infrastructure ▸ Need a control system to manage the interface between grid and satellite operations. ▸ The control system is likely to be far more complex than for existing satellites. The architecture of the control system, particularly whether it is centralised or decentralised, is a key question.		

International TRL	6	International TRL justification	Many satellites and space stations have been developed and operated from the ground (for example Deep Space 1 (NASA, 2019)), however they are much less complex than what is foreseen for SBSP to manage the structural response, power and security of the system. Aspects of the power management are demonstrated on existing commercial solar PV stations (Ranjan, 2019).
International major engineering barriers	▸ The control system is likely to be far more complex than for existing satellites. The architecture of the control system, particularly whether it is centralised or decentralised, is a key question.		

	- Need a control system to manage the interface between grid and satellite operations.

Technically feasible	Yes	Feasibility justification	It is possible to apply existing satellite control technology to SBSP with sufficient enhancements to manage the size of the structure.
Difficulty	Medium	Difficulty justification	Similar technology is in use for current satellites. To adapt to the much larger scale developments must be made however these are likely to be iterative improvements on current control systems.

B.1.15 SYSTEM ELEMENT: GROUND COMMUNICATIONS

Critical enabling technology: Space telemetry link

Description: Transmit data to the satellite and receive data from the satellite for the purposes of control and system monitoring

Figure 22 – Example of satellite radio dish for communications [15].

UK TRL	5	UK TRL justification	Surrey Satellites develop small scale satellites and operate them (Surrey Satellites, n.d.). The communication systems are therefore used to communicate with space from the ground, however they are likely to be lower bandwidth and security than that required to operate complex critical national infrastructure.
UK major engineering barriers	‣ More robust communication approach required as SBSP will be Critical National Infrastructure. ‣ Need a communication link to manage the interface between grid and satellite operations. ‣ The communication system is likely to need to have greater bandwidth than existing satellite systems. The architecture of the communications system, particularly whether it is centralised or decentralised, is a key question.			

International TRL	6	International TRL justification	Many satellites and space stations have been developed and operated in space (for example Deep Space 1 (NASA, 2019)). The communication systems are therefore used in space, and given the complexity of some satellites and the needs of manned spaceflight they may have similar bandwidth and security to that required to operate complex critical national infrastructure.
International major engineering barriers	‣ Limited experience of creating a cohesive communication link between national grid requirements and satellite operations. ‣ The communication system is likely to need to have greater bandwidth than existing satellite systems. The architecture of the			

	communications system, particularly whether it is centralised or decentralised, is a key question.

Technically feasible	Yes	Feasibility justification	Technology transfer from similar application with other satellites.
Difficulty	Low	Difficulty justification	This will largely require transfer of technology for similar industries such as terrestrial solar with adaptations to meet differing requirements such as the interface with a satellite system.

B.1.16 SYSTEM ELEMENT: SATELLITE OPERATION

Critical enabling technology: Satellite control system interface

Description: Interface to the control function of the satellite

Figure 23 – Main Control Room at ESA's Space Operations Centre [16].

UK TRL	5	UK TRL justification	Surrey Satellites develop small scale satellites and operate them (Surrey Satellites, n.d.). The operation systems are therefore used to communicate with space from the ground, however they are likely to be lower bandwidth and security than that required to operate complex critical national infrastructure.
UK major engineering barriers	‣ Limited experience operating large, complex satellites that are Critical National Infrastructure ‣ A more complex interface will be required and this complexity will likely bring additional engineering challenges to maintain control over a large satellite of national significance. ‣ Integration of control interface with power grid.		

International TRL	6	International TRL justification	Many satellites and space stations have been developed and operated in space (for example Deep Space 1 (NASA, 2019)). The communication systems are therefore used in space, and given the complexity of some satellites and the needs of manned spaceflight they may have similar bandwidth and security to that required to operate complex critical national infrastructure.
International major engineering barriers	‣ Integration of control interface with power grid. ‣ Limited experience operating large, complex satellites that are Critical National Infrastructure		

Technically feasible	Yes	Feasibility justification	Technology transferred from similar applications.
Difficulty	Medium	Difficulty justification	Operating a satellite on the proposed scale will required development of this capability but it is deemed similar to other technological developments.

B.1.17 SYSTEM ELEMENT: SATELLITE MAINTENANCE

Critical enabling technologies: a) Remotely operated/ Automated/ autonomous space robotics, b) Transit to GEO and rendezvous

Description: Inspect, clean, remove, replace and repair components on the satellite. Replenish fluids and other consumables

Figure 24 – SpaceX Dragon connected to the Canadarm2 robotic arm at the International Space Station, illustrating methods of satellite maintenance [17].

UK TRL	3	UK TRL justification	The UK is involved in a variety of research and development projects to support satellite maintenance or similar activities including PERASPERA Space Robotic Technologies which has involvement from Thales Alenia Space (Horizon 2020, 2020) and focussed packages including European Robotic Orbital Support Services (EROSS) (PIAP Space, 2019), Modular Spacecraft Assembly and Reconfiguration Demonstrator (MODAR) (Deremetz, 2019) and the End-of-Life Service by Astroscale (ELSA) programme ((UK Research and Innovation, n.d.). Other aspects include additive manufacture in space being investigated by Cranfield University (Nathan, 2019). While many of these projects are design projects, they are yet to be tested in laboratory conditions.
UK major engineering barriers	▸ Limited experience operating, manipulating robotics in space – whether tele-operated, automated or autonomous. ▸ Unknown satellite failure mechanisms and maintenance burden of large structures in space ▸ Mass production robotic manufacturing likely required to maintain large satellites. ▸ Level of automation/autonomy in robots is currently likely to be insufficient to conduct maintenance without human intervention and the associated communication complexities		

	▸ No established concept of operation for delivery and storage of spare parts in GEO or similar orbit.

International TRL	5	International TRL justification	PERASPERA is a European project and therefore is also considered for international TRL. Mission Extension Vehicle 1 (MEV-1) was built by Northrop Grumman docked with a geostationary satellite in 2020 to fuel and steer the satellite (Sheetz, 2020). Since then MEV-2 has also been launched (Corbett, 2020). While this is an element of the maintenance required for SBSP, it does not include automated manipulation of components and is therefore not fully representative.
International major engineering barriers	▸ Limited experience operating manipulating robotics in space that are automated or autonomous. ▸ Unknown satellite failure mechanisms and maintenance burden of large structures in space ▸ Mass production robotic manufacturing likely required to maintain large satellites. ▸ Level of automation/autonomy in robots is currently likely to be insufficient to conduct maintenance without human intervention and the associated communication complexities. ▸ No established concept of operation for delivery and storage of spare parts in GEO or similar orbit.		

Technically feasible	Yes	Feasibility justification	Feasible with continued technology development and experience of maintaining structures in space.
Difficulty	Very High	Difficulty justification	Currently there are significant unknowns in this concept of operations. The scale required will be far greater than on any similar space technology.

B.1.18 SYSTEM ELEMENT: POWER STATION OPERATION

Critical enabling technology: Ground station control interface

Description: Interface to control the function of the ground station

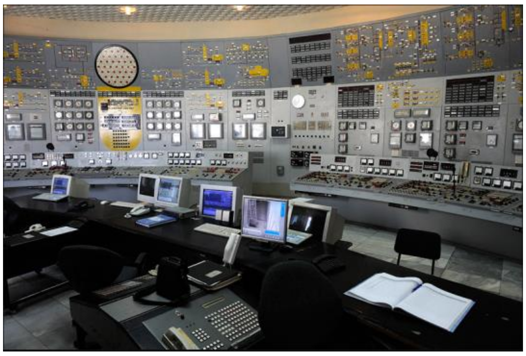

Figure 25 – Example of a power station control room [18].

UK TRL	7	UK TRL justification	Terrestrial solar PV stations have very similar systems for power control as those foreseen for SBSP. The systems for control and operation and provided by companies such as GE and Siemens, both of which operate within the UK (General Electric, n.d.), (Siemens, 2020).
UK major engineering barriers	‣ Incorporating a new type of grid input technology to the national energy mix and controlling it.		

International TRL	7	International TRL justification	Terrestrial solar PV stations have very similar power operations as those foreseen for SBSP. The largest PV stations in commercial use have a capacity in excess of 2GW (Ranjan, 2019).
International major engineering barriers	‣ Incorporating a new type of grid input technology to the national energy mix and controlling it.		

Technically feasible	Yes	Feasibility justification	Similar to power stations currently in operation.
Difficulty	Low	Difficulty justification	This will largely require transfer of technology for similar industries such as terrestrial solar with adaptations to meet differing requirements.

B.1.19 SYSTEM ELEMENT: SATELLITE MANUFACTURE (GROUND)

Critical enabling technology: Satellite manufacture

Description: Manufacture the satellite

Figure 26 – NASA's ground-based testing of satellite servicing technologies [19].

UK TRL	5	UK TRL justification	Surrey Satellites develop and manufacture small scale satellites and operate them (Surrey Satellites, n.d.). The UK Government has also invested in OneWeb satellite manufacturers (PTI, 2020). These satellites are orders of magnitude smaller than the SBSP designs proposed. Therefore the basic elements of satellite manufacture are integrated, into something like the end environment, but this is only at pilot scale. The UK also has microchip manufacturing capability since 1967 (Electronics Weekly, 2007) and the dedicated Compound Semiconductor Applications Catapult.
UK major engineering barriers	‣ Capacity for mass production of space grade parts ‣ Use of rare raw materials, depending on satellite design, including those that may not be found naturally within the UK		

International TRL	5	International TRL justification	The International Space Station is the largest satellite manufactured with a length of 109 meters and a mass of 420 tonnes (NASA, 2020). This is at least one order of magnitude smaller than the SBSP designs proposed. Therefore the basic elements of satellite manufacture are integrated, into something like the end environment, but this is only at pilot scale.
International major engineering barriers	‣ Capacity for mass production of space grade parts ‣ Use of rare raw materials, depending on satellite design		

Technically feasible	Yes	Feasibility justification	Scaling up production facilities would be required but has been shown to be successful in other industries.
Difficulty	High	Difficulty justification	A significant shift in the scale of space manufacture is required to deliver the volumes necessary to build full scale SBSP satellites.

B.1.20 SYSTEM ELEMENT: SPACE LIFT

Critical enabling technology: Heavy lift space launch

Description: Lift the components/sub-assemblies of the satellite into orbit (assumed Geostationary Earth Orbit) including transit from LEO to GEO.

Figure 27 – Launch of the SpaceX Falcon Heavy Rocket in 2018 [20].

UK TRL	3	UK TRL justification	The UK has previously developed rockets which have launched UK satellites, however this was last done in 1970s (Krebs, 2019) using very small payloads. Currently Reaction Engines are planning testing of the Synergetic Air Breathing Rocket Engine (SABRE), which would form one element of a UK space capability (Reaction Engines, 2020), The basic components of the resulting platform are not yet integrated.
UK major engineering barriers	▸ Limited experience with space launch systems and large space programmes, particularly when compared to other nations. ▸ Lack of capacity to launch the mass/volume required. ▸ UK latitude means that it is less well suited for launch, depending on the final orbit being targeted. Equatorial orbits are penalised, whereas polar orbits are not.		

International TRL	8	International TRL justification	Space X has flown systems lifting 64 tonnes to LEO and 27 tonnes to Geostationary Transfer Orbit (GTO) (Space X, 2020). While it may take many flights to lift the total mass required to assemble a full SBSP system, this system has been proven to work and could be the final form used for SBSP.
International major engineering barriers	▸ Current lack of capacity to launch the volume and mass required.		

Technically feasible	Yes	Feasibility justification	Continued development of space transportation required, extending current trajectory of total annual capacity.
Difficulty	High	Difficulty justification	Large increase in capacity required to achieve full scale SBSP satellites.

B.1.21 SYSTEM ELEMENT: IN-ORBIT ASSEMBLY

Critical enabling technology: Remotely operated/ Automated/ autonomous space robotics

Description: Integrate components/sub-assemblies in space

Figure 28 – Attachment of the Pressurized Mating Adapter-3 to the International Space Station using the Canadarm2 robotic arm [21].

UK TRL	3	UK TRL justification	In-orbit assembly is analogous to the replacing of parts in-orbit, and therefore shares characteristics of satellite maintenance. The UK is involved in a variety of research and development projects to support satellite maintenance or similar activities including PERASPERA Space Robotic Technologies which has involvement from Thales Alenia Space (Horizon 2020, 2020) and focussed packages including European Robotic Orbital Support Services (EROSS) (PIAP Space, 2019), Modular Spacecraft Assembly and Reconfiguration Demonstrator (MODAR) (Deremetz, 2019) and the End-of-Life Service by Astroscale (ELSA) programme ((UK Research and Innovation, n.d.). Other aspects include additive manufacture in space being investigated by Cranfield University (Nathan, 2019). While many of these projects are design projects, they are yet to be tested in laboratory conditions.
UK major engineering barriers	‣ Limited experience operating robotics in space. ‣ Large scale robotic manufacturing likely required to assemble large satellites in acceptable timeframes. ‣ Challenges of modular assembly while retaining structural stiffness. ‣ Level of automation/autonomy in robots is currently likely to be insufficient to conduct maintenance without human intervention and the associated communication complexities. ‣ Limited experience of in-orbit assembly. ‣ Ensuring design and manufacturing techniques are validated and risks are well understood.		

	‣ No established concept of operation for delivery and storage of parts in GEO or similar orbit.

International TRL	5	International TRL justification	In-orbit assembly is analogous to the replacing of parts in-orbit, and therefore shares characteristics of satellite maintenance. The International Space Station (ISS) is the largest assembled structure in space (NASA, 2020). PERASPERA is a European project and therefore is also considered for international TRL. Mission Extension Vehicle 1 (MEV-1) was built by Northrop Grumman docked with a geostationary satellite in 2020 to fuel and steer the satellite (Sheetz, 2020). Since then MEV-2 has also been launched (Corbett, 2020). While this is an element of the assembly required for SBSP, it does not include automated manipulation of components and is therefore not fully representative.
International major engineering barriers	‣ Limited experience operating manipulating robotics in space ‣ Large scale robotic manufacturing likely required to assemble large satellites in acceptable timeframes. ‣ Challenges of modular assembly while retaining structural stiffness ‣ Level of automation/autonomy in robots is currently likely to be insufficient to conduct maintenance without human intervention and the associated communication complexities. ‣ Ensuring design and manufacturing techniques are validated and risks are well understood.		

Technically feasible	Yes	Feasibility justification	Significant increases in size and therefore complexity means a large number of robots will likely be required for assembly. These robots as yet are not yet designed, neither are the structures that they need to manipulate. It has not been proven than it is feasible for them to operate independently and this poses a significant risk to technical feasibility.
Difficulty	Very High	Difficulty justification	Currently there are significant unknowns in this concept of operations. The scale required will be far greater than on any similar space technology.

B.1.22 SYSTEM ELEMENT: SATELLITE DECOMMISSION

Critical enabling technology: Remotely operates/automated/autonomous space robotics, controlled descent, re-entry shielding, in-orbit recycling

Description: Return the satellite to an acceptable long-term state, assumed to be with it removed from orbit and with the constituent materials reclaimed/stored.

Figure 29 - Attachment of the Pressurized Mating Adapter-3 to the International Space Station using the Canadarm2 robotic arm [21]. Similar procedures in reverse could provide an option for part of the decommissioning.

UK TRL	2	UK TRL justification	Satellites produced by the UK have been small and generally decommissioned through destruction as they decay from orbit, such as the Ariel satellites (NASA, 2020). This is inappropriate for structures of the size under consideration, and decommissioning research has not been initiated. Possibilities considered include graveyard orbits and in-space recycling.
UK major engineering barriers	‣ A plan for decommissioning is required by law before launch and therefore must be considered during the design stage, and for each space trial/demonstration. This presents challenges as the state of technology during the decommissioning period is unknown. ‣ Bringing an object this large back to Earth has not yet been achieved, either as a whole mass or discrete pieces. ‣ There is no clear method established for decommissioning large satellites in space. ‣ Alternatives include graveyard orbits, disassembly, perpetual re-use and in-orbit recycling. Leaving the object in space either in its operational orbit or a graveyard orbit may not be considered decommissioning and is unlikely to at the time of decommissioning with the increasing risk of space debris.		

International TRL	2	International TRL justification	The largest satellites every decommissioned are many orders of magnitude smaller than SBSP satellites, examples weighing only 10.5 tonnes (Chow, 2011) . Possibilities considered include graveyard orbits and in-space recycling. Decommissioning research has not yet been initiated.
International major engineering barriers	‣ A plan for decommissioning is required by law before launch and therefore must be considered during the design stage, and for each space trial/demonstration. This presents challenges as the state of technology during the decommissioning period is unknown. ‣ Bringing an object this large back to Earth has not yet been achieved, either as a whole mass or discrete pieces. ‣ There is no clear method established for decommissioning satellites in space ‣ Alternatives include graveyard orbits, disassembly, perpetual re-use and in-orbit recycling. Leaving the object in space either in its operational orbit or a graveyard orbit may not be considered decommissioning and is unlikely to at the time of decommissioning with the increasing risk of space debris.		

Technically feasible	Yes	Feasibility justification	This technology needs considerable further development before SBSP can be launched. Currently there is no clear pathway to achieving this.
Difficulty	Very High	Difficulty justification	Currently there are significant unknowns in this concept of operations. The scale required will be far greater than on any similar space technology.

B.1.23 SYSTEM ELEMENT: RECTENNA MANUFACTURE

Critical enabling technology: Rectenna manufacture

Description: Manufacture the rectenna

Figure 30 – Manufacture of components for space systems [22].

UK TRL	3	UK TRL justification	No specific UK experiments have taken place, therefore UK TRL is informed by research in the international public domain.
UK major engineering barriers	‣ UK has limited experience in rectenna manufacture which would need to be done at scale to achieve the size of rectenna required		

International TRL	5	International TRL justification	Others have claimed TRLs of between 4 and 6 based on the form of the rectenna (Mankins, 2011). Mitsubishi Heavy Industries has demonstrated a transmission of 10kW over a distance of 500m using microwaves on the ground (Ackerman, 2015). This is small scale but it is in a representative environment (i.e. on the ground).
International major engineering barriers	‣ Scale of production would need to significantly increase.		

Technically feasible	Yes	Feasibility justification	Increase in manufacturing volume required, however the technology is similar to others that are produced at scale.
Difficulty	Medium	Difficulty justification	The scale of manufacture is large but is analogous to other technologies.

B.1.24 SYSTEM ELEMENT: POWER FACILITY CONSTRUCTION

Critical enabling technology: Power facility station construction

Description: Construct and commission the ground station

Figure 31 – Early stages of construction of Hinkley Point C power station [23].

UK TRL	7	UK TRL justification	Terrestrial solar PV stations have very similar power facilities as those foreseen for SBSP. Currently the largest solar PV station in the UK is the Shotwick Solar Farm with a power rating of 72.2MW (British Solar Renewables, n.d.). The largest solar PV farm in the UK will be the 350MW Cleve Hill Solar Park, due to start in 2021 (Cleve Hill Solar Park, 2020). The UK has electrical machinery installed at power stations up to 3.96GW, as used at Drax (Power Stations of the UK, 2019),
UK major engineering barriers	No significant engineering barriers foreseen.		

International TRL	7	International TRL justification	Terrestrial solar PV stations have very similar power facilities as those foreseen for SBSP. The largest PV stations in commercial use have a capacity in excess of 2GW (Ranjan, 2019).
International major engineering barriers	No significant engineering barriers foreseen.		

Technically feasible	Yes	Feasibility justification	Similar to terrestrial power construction.
Difficulty	Low	Difficulty justification	This will largely require transfer of technology for similar industries such as terrestrial solar with adaptations to meet differing requirements.

B.1.25 SYSTEM ELEMENT: CONTROL STATION CONSTRUCTION

Critical enabling technology: Control and communication facility construction

Description: Construct and commission the station for communication

Figure 32 – Assembly of a radio antenna used for extra-terrestrial communications [24].

UK TRL	5	UK TRL justification	Surrey Satellites develop small scale satellites and operate them (Surrey Satellites, n.d.). Therefore the UK has experience in building control stations. However they are likely to be lower bandwidth and security than that required to operate complex critical national infrastructure.
UK major engineering barriers	No significant engineering barriers foreseen.		

International TRL	6	International TRL justification	Many satellites and space stations have been developed and operated in space (for example Deep Space 1 (NASA, 2019)). Therefore there is international experience in building control stations. Given the complexity of some satellites and the needs of manned spaceflight they may have similar bandwidth and security to that required to operate complex critical national infrastructure.
International major engineering barriers	No significant engineering barriers foreseen.		

Technically feasible	Yes	Feasibility justification	Control stations for critical satellites currently exist.
Difficulty	Low	Difficulty justification	This will largely require transfer of technology for similar industries such as terrestrial solar with adaptations to meet differing requirements.

B.1.26 SYSTEM ELEMENT: GROUND STATION DECOMMISSIONING

Critical enabling technology: Terrestrial systems decommissioning

Description: Return the ground station to an acceptable long-term state

Figure 33 – Decommissioning Bradwell A Power Station in the UK [25].

UK TRL	7	UK TRL justification	The decommissioning is likely to be analogous to that of other satellite ground stations and power stations such as terrestrial solar PV stations/aerials. The UK has decommissioned satellite operating centres and power stations previously. The most onerous of these are the decommissioning of nuclear power stations, which are much more challenging than SBSP is likely to be (UK Government, n.d.).
UK major engineering barriers	No significant engineering barriers foreseen.		

International TRL	7	International TRL justification	The decommissioning is likely to be analogous to that of other satellite ground stations and power stations such as terrestrial solar PV stations/aerials. There is international experience of decommissioning satellite operating centres and solar power stations (Ludt, 2019).
International major engineering barriers	No significant engineering barriers foreseen.		

Technically feasible	Yes	Feasibility justification	Similar to decommission of other non-nuclear terrestrial structures.
Difficulty	Low	Difficulty justification	The scale of decommissioning is large but likely low density so analogous to other technologies.

ANNEX C - TECHNOLOGY ROADMAPS

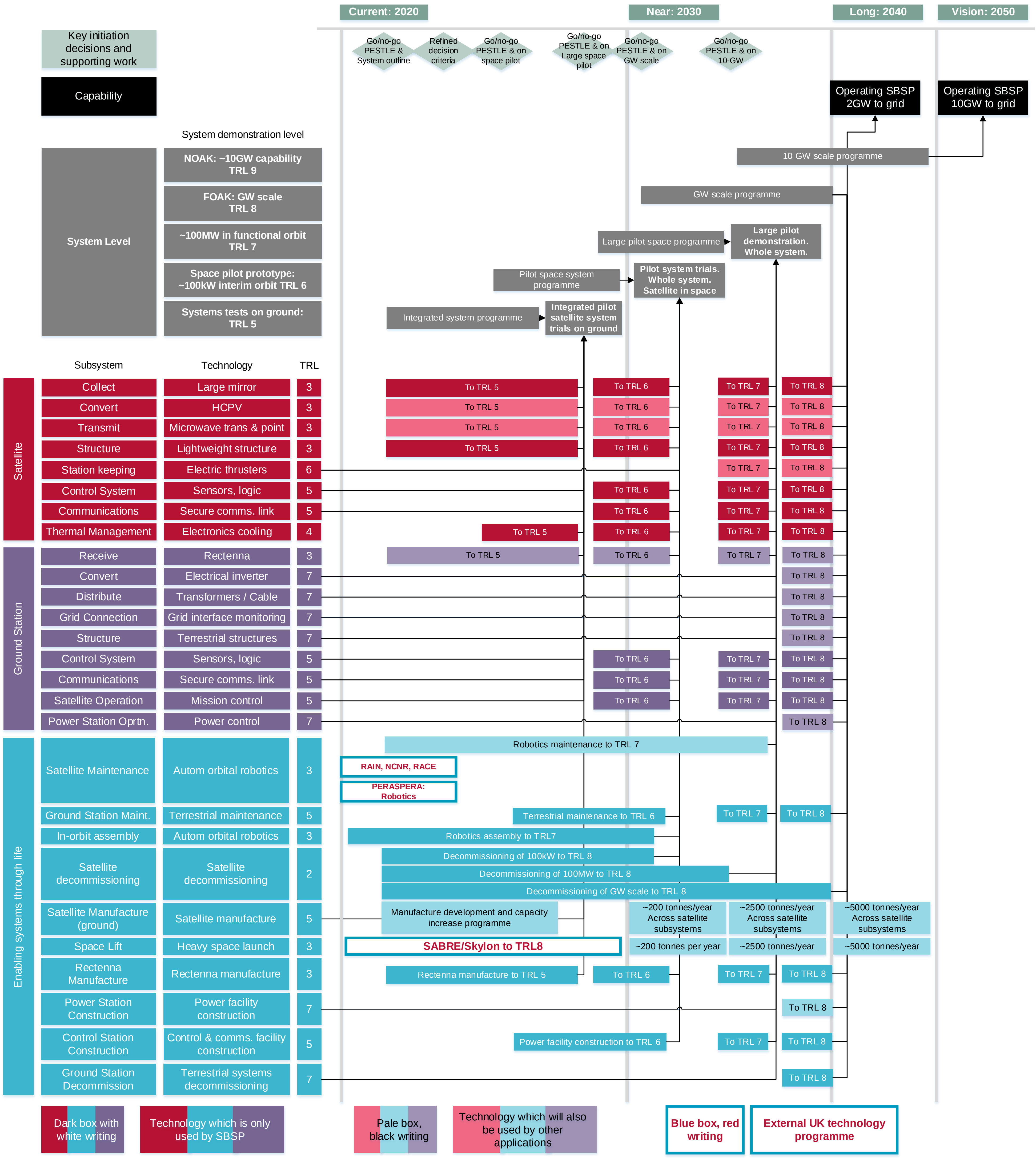

Figure 34 - UK roadmap to Space Based Solar Power by 2050

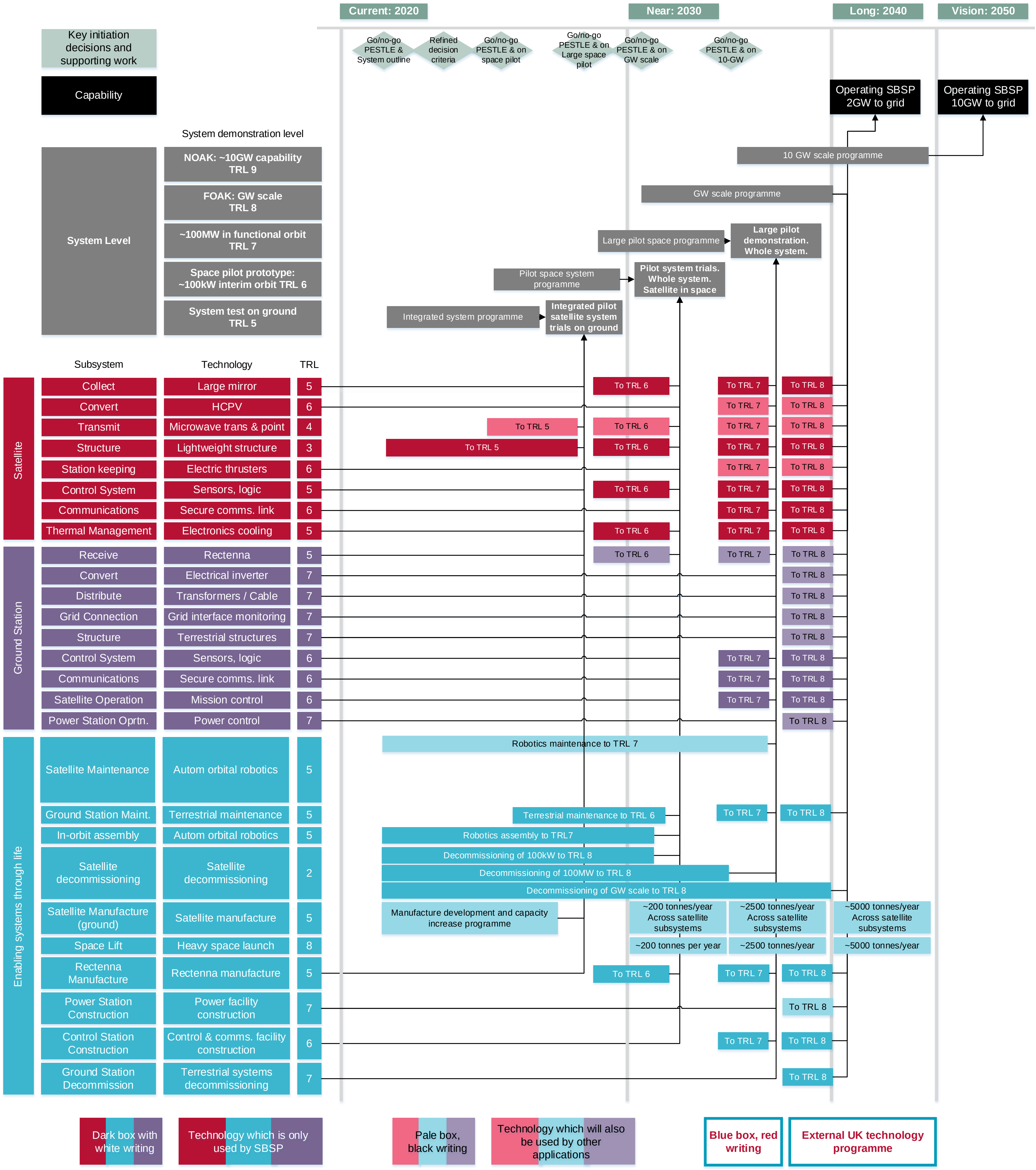

Figure 35 - International roadmap to Space Based Solar Power by 2050

Frazer-Nash Consultancy Ltd
The Cube
1 Lower Lamb Street
Bristol
BS1 5UD

T +44 (0)117 9226242
F +44 (0)117 9468924

www.fnc.co.uk

Offices at:
Bristol, Burton-on-Trent, Dorchester,
Dorking, Glasgow, Plymouth, Warrington
and Adelaide