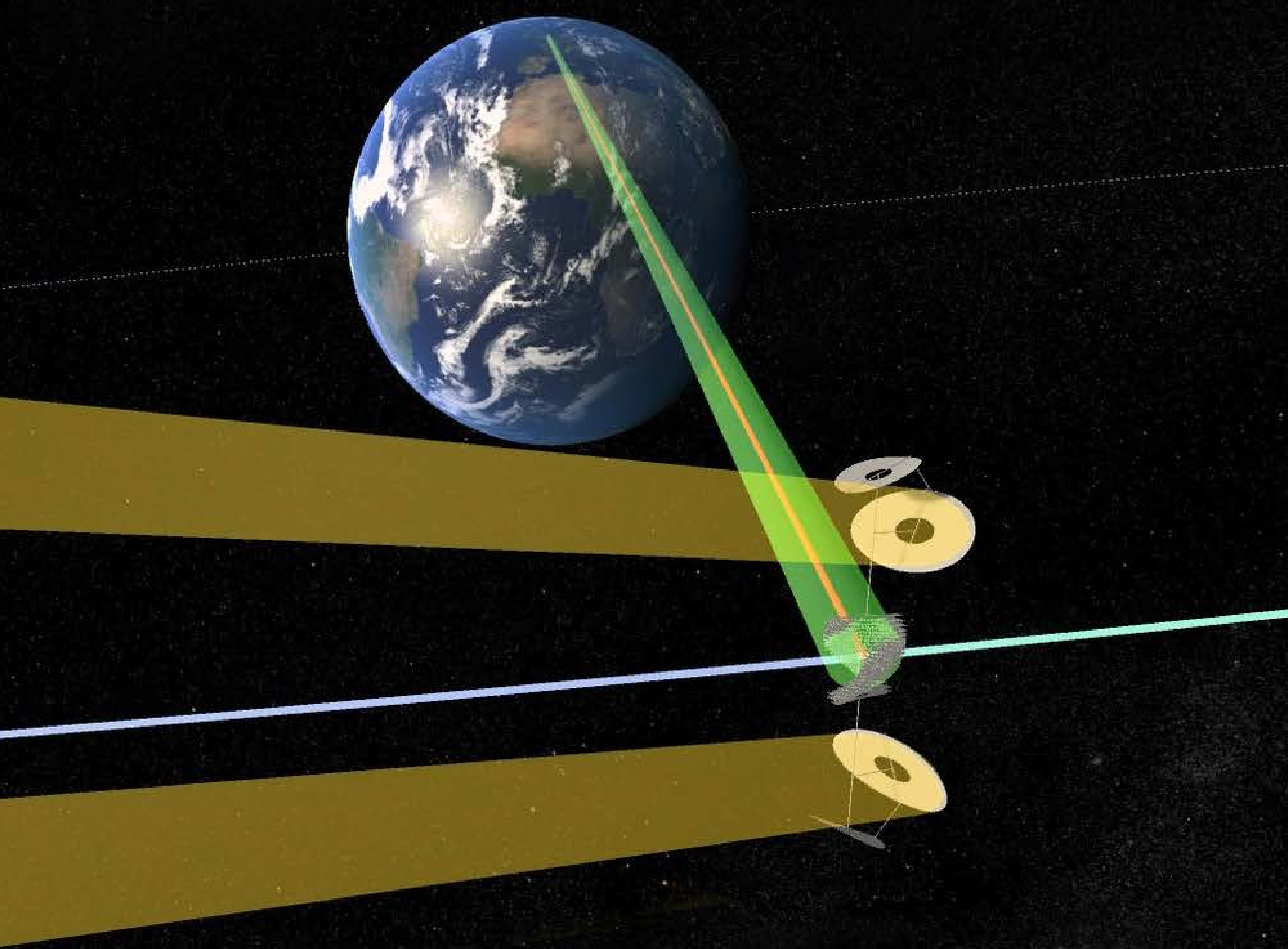
Report

Space Based Solar Power

De-risking the pathway to Net Zero



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Systems • Engineering • Technology

> *There is 100 times more solar energy available from a narrow strip around the earth at Geostationary Earth Orbit (GEO), than the forecast global energy demands of humanity in 2050.*

Executive Summary

The Government's legal commitment to Net Zero by 2050 is ambitious. Significant risks remain in reaching the decarbonisation goals, and these challenges are recognised.

Frazer-Nash Consultancy, under contract for the Department for Business, Energy and Industrial Strategy (BEIS) has undertaken an independent study into the technical feasibility, cost and economics of Space Based Solar Power, as a novel generation technology to help the UK deliver its Net Zero policy.

Space Based Solar Power comprises a constellation of very large satellites in a high earth orbit, where the sun is visible over 99% of the time, collecting solar power and beaming it securely to a fixed point on the earth. Its main attribute is the ability to deliver clean, baseload energy, day and night throughout the year and in all weathers.

Recent technology and conceptual advances have made the concept both viable and economically competitive.

This study concludes:

- Space Based Solar Power is technically feasible, and could support Net Zero pathways;
- It is affordable, with a competitive Levelised Cost of Electricity;
- Development of this technology would bring substantial economic benefits for the UK.

Recommendations are made to:

- Incorporate Space Based Solar Power into relevant Government Policies, including Net Zero and the National Space Strategy;
- Initiate a staged technology development and demonstration programme.

Space Based Solar Power aligns well with key government priorities:

- Delivering Net Zero by 2050
- UK global environmental leadership
- Security of critical infrastructure
- High technology growth and jobs
- Growing our space capability
- Economic prosperity and levelling up

> *Space Based Solar Power gives the UK new options to deliver Net Zero.*

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Space Based Solar Power could offer new options to de-risk Net Zero

Orbital demonstrator by
2031

Baseload Energy
24/7/365

Operational system by
2040

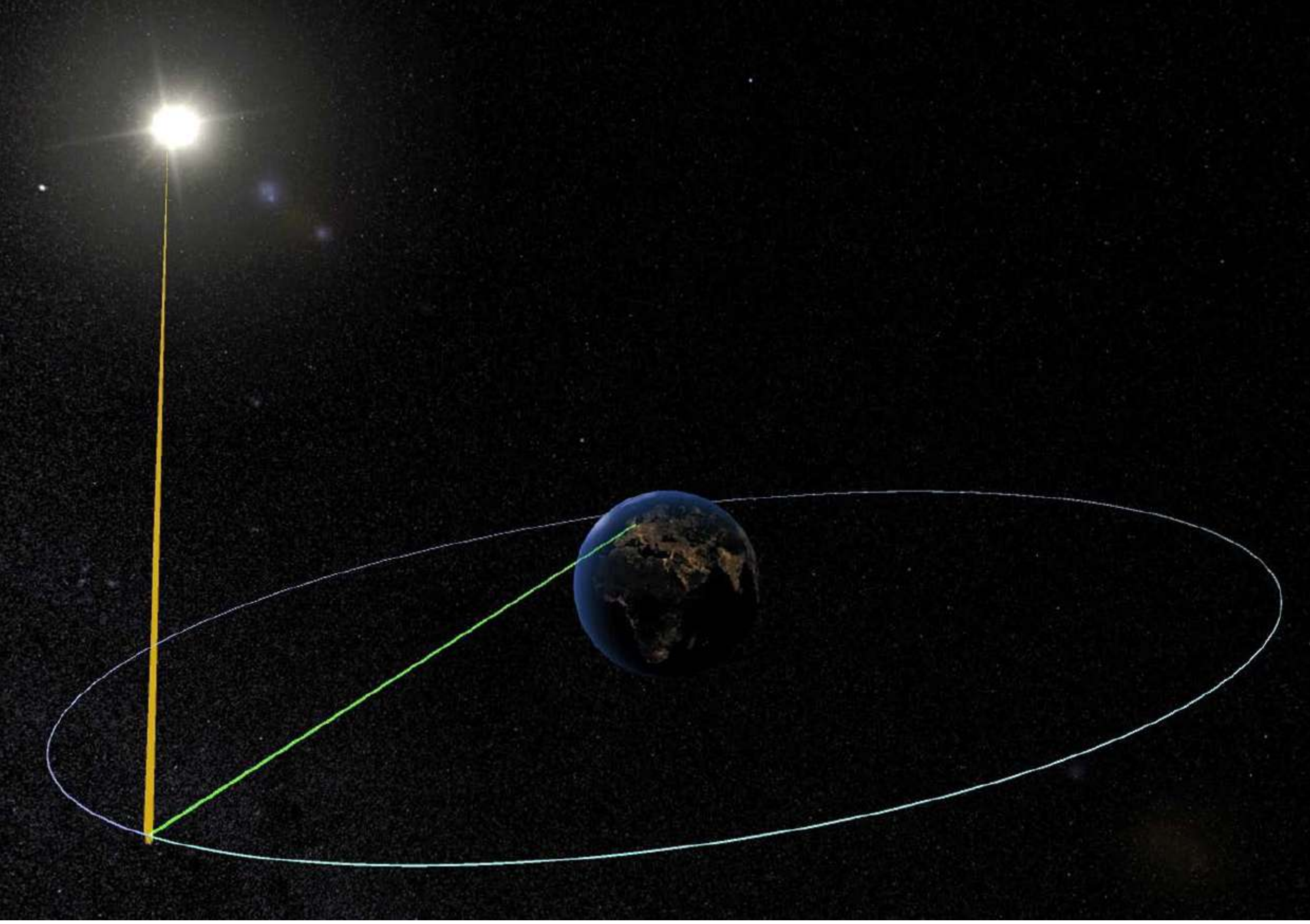
Requires reusable low cost space launch

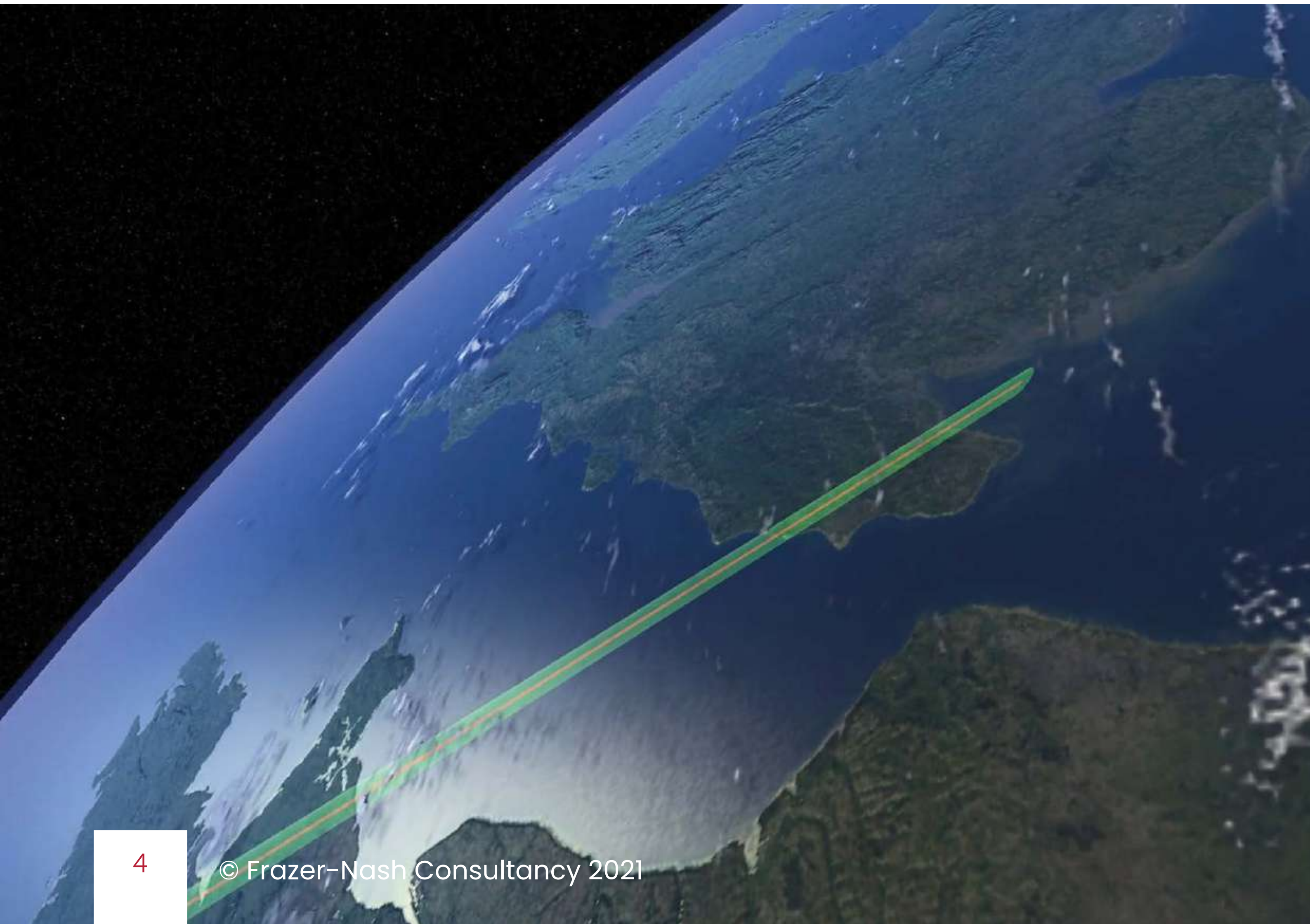
Exellent grid integration
Despatchable and scalable

Technology is feasible but immature

COMPETITIVE
Levelised Cost Of Electricity

SUSTAINABLE
Clean Energy





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Contents

leading the way

The UK is leading the way with Net Zero

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> *The technical and political challenges of Net Zero are substantial, requiring new and innovative technology solutions.*

1

Why do we need new energy sources?

There is an urgent need to develop new sources of clean energy that are sustainable, affordable, secure and scalable.

1.1. The global context

Global energy demand is forecast to double in the next 30 years. At the same time, climate change risks additional pressure on land and resources, with all the geo-political consequences that may flow from this. There is an urgent need to develop new sources of clean energy that are sustainable, affordable, secure and scalable.

1.2. Net Zero is challenging

The UK is demonstrating environmental leadership across the globe with Net Zero, the Government's legal commitment to decarbonise the economy by 2050. This is an ambitious goal, with substantial risks, and the scale of these challenges is recognised. Current energy scenario modelling does not consider Space Based Solar Power.

The modelling suggests that it is only possible to achieve Net Zero if:

- The amount of nuclear and biomass generation is substantially increased to utilise all the suitable sites;
- Carbon Capture and Storage (CCS) reaches very high capture rates; and
- Significant changes in technology or society are pursued that make increasingly speculative options more viable.

Substantial baseload generation is required within a mix of energy technologies.

The intermittency of the main renewable technologies requires energy storage or other underpinning baseload generation.

The political and technical challenges of moving to a truly sustainable clean energy economy, whilst preserving our prosperity, should not be underestimated. It is recognised that we need to urgently explore new baseload energy technologies to contribute to the delivery of Net Zero.

Space Based Solar Power is a renewable technology which provides continuous baseload power without intermittency, and could be available at large scale. It therefore warrants further exploration as it could offer new options and contribute to the Net Zero pathways.

1.3. The characteristics required of new energy sources

At the start of this study, BEIS highlighted a number of criteria that a new energy technology should meet to be seriously considered.

- It has to be **clean**, no CO_2 or other waste.
- It must provide **baseload power**, and deliver **affordable energy** for homes and industry.
- It must be **secure**, in terms of both reliability and UK sovereign control and it should be **resilient** to natural disasters and terrorist attack.
- The fuel supply should be **scalable, abundant** and **sustainable**.
- It should not take up too much **land area**.
- It must be **safe**, and it should **integrate** well into the existing power distribution grid.
- It should be **deliverable in time** to make a substantial contribution to UK electricity generation by 2050.
- And importantly, the development and operation should be economically beneficial, creating and sustaining **high value jobs** across the UK.

1.4. About this report

This study is an independent assessment of whether Space Based Solar Power is technically feasible, affordable and could help the UK deliver Net Zero.

Over the six month study period we have sought to identify concerns, engineering barriers and broader risks, together with the potential benefits and alignment with government priorities. We have engaged widely through workshops and structured conversations with a range of leaders and experts at Chief Technology Officer level across the UK space and energy sectors, the UK Space Agency, the Ministry of Defence, UK Research and Innovation, and leading Universities.

Additionally, we have consulted extensively with John Mankins (Mankins Space Technology) and Ian Cash (International Electric Co. Ltd), who are two international authorities on Space Based Solar Power.

This document is a high level summary of our detailed study reports[1], and intended for policy makers.

Hitherto, Space Based Solar Power has not been considered by the UK. Its proponents claim that it is now becoming technically feasible and economically viable. Could it play a part in de-risking the pathways to Net Zero for the UK?

[1] Phase 1 - Technical Feasibility - FNC 004456-51057R Issue 1.0
Phase 2 - Economic Feasibility - FNC 004456-51624R Issue 1.0

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> *Clean baseload power is essential for our future energy grid.*

The global need for innovation in clean energy

space based solar power

Space Based Solar Power has the potential to provide a major contribution to energy generation across the globe.

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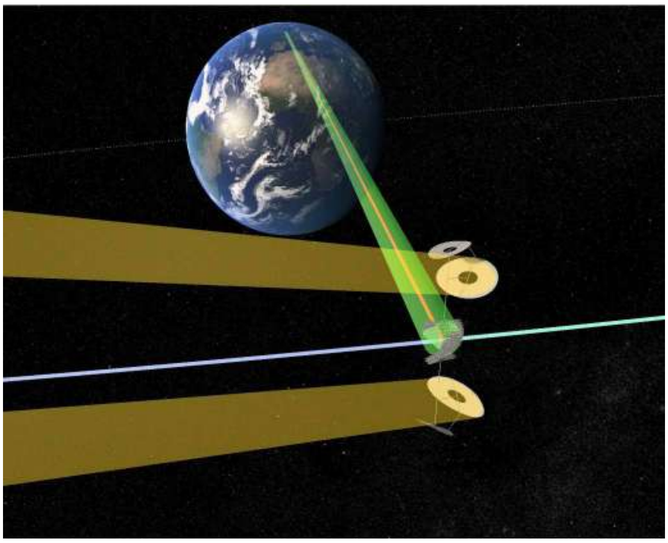
2

Why Space Based Solar Power?

Scalable, base load energy, with a range of desirable characteristics.



2.1. Offering new options to deliver Net Zero

Satellites in geosynchronous orbit are illuminated by the sun for more than 99% of the time with a solar intensity substantially greater than received on the ground in the UK.

Space Based Solar Power is the concept of collecting this abundant solar power in orbit, and beaming it securely to a fixed point on the earth. Its main advantage over wind and terrestrial solar energy is the ability to deliver energy day and night throughout the year and in all weathers.

It has good grid integration characteristics and is safe, resilient and secure. It is scalable, and could make a major contribution to the global need for abundant, affordable clean energy. As part of a mix of energy technologies, it offers new options for the UK and is able to support the UK drive for Net Zero.

Other benefits include the ability to beam power to other nations, either as an energy export, or as part of our overseas development aid, or to support humanitarian disaster areas.

Space Based Solar Power can deliver all the demanding characteristics set out by BEIS for a new energy technology. This study confirms the claims of proponents, that the technology is becoming both viable and affordable. It offers potentially beneficial characteristics summarised in the following table. Note that this study has principally focussed on the technical and economic aspects, and further study into these broader characteristics is recommended.

> *… solar insolation in space – the amount of power available over a given area – is substantially greater than available on earth at the UK latitude.*

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Energy generation	Continuous power generation, 24/7, 365 days/year Gigawatt levels of baseload energy generation Green hydrogen generation for the transport sector
Security and economics	Security and resilience to political or terrorist action Affordable LCOE for homes and industry Long term security of fuel supply
Grid integration	Readily integrated with existing grid infrastructure Low intermittency, high predictability Despatchable, high load factor
Environmental impact*	Fully sustainable, renewable energy source Low carbon payback period Low environmental impact (footprint, land use)
Delivering Net Zero	Roadmap for orbital demonstrator by 2031 Operational system could be developed by 2040 Scalable to provide substantial proportion of energy
Flexible energy*	Export opportunities for energy and technology Power for humanitarian disaster relief Power for spacecraft and lunar operations

Space Based Solar Power offers a range of desirable characteristics

* These elements are wider claims made for the technology. Whilst they appear reasonable, they have not been assessed in detail during this study.

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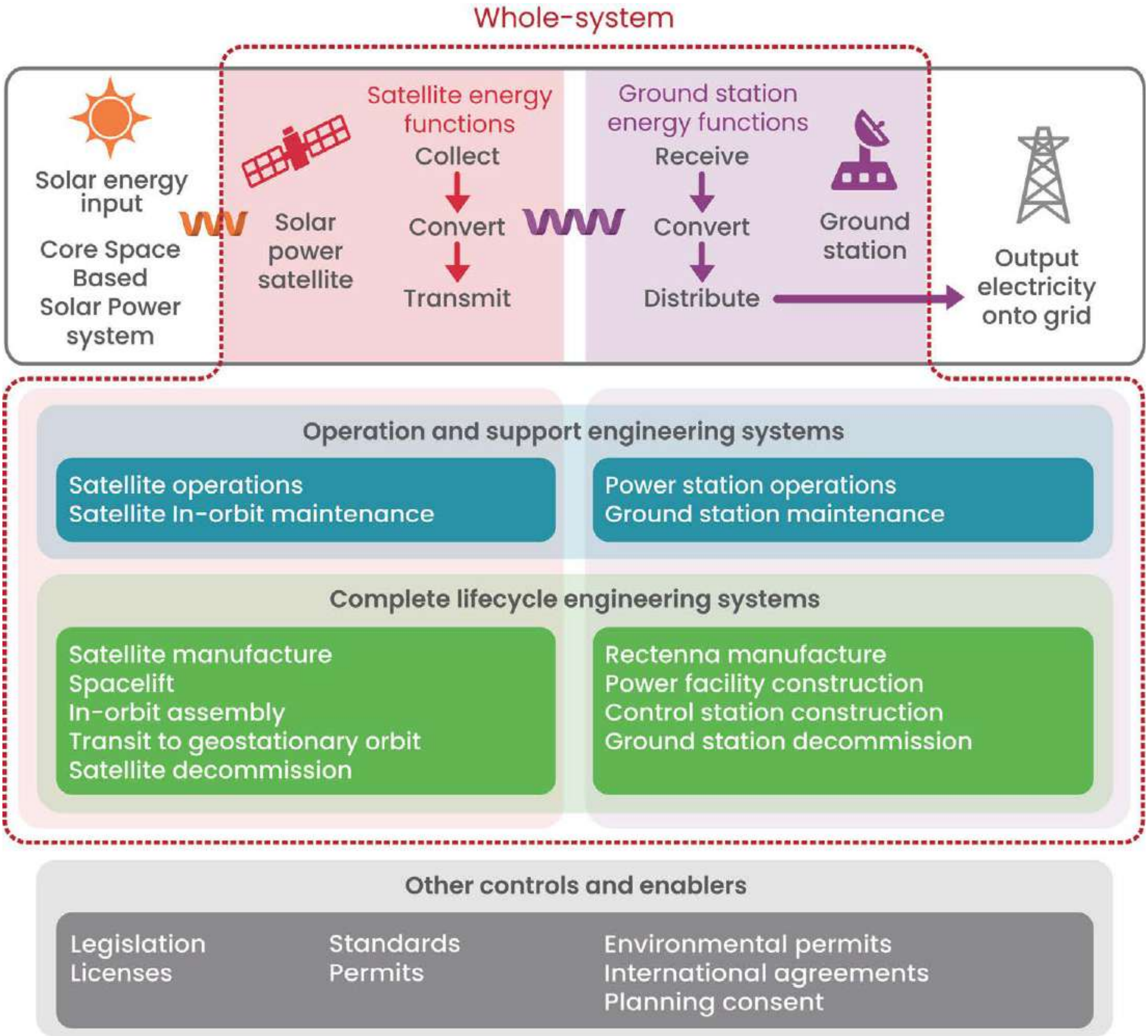
Whole-system
Solar energy input
Core Space Based Solar Power system
Solar power satellite
Satellite energy functions
Collect
Convert
Transmit
Ground station energy functions
Receive
Convert
Distribute
Ground station
Output electricity onto grid
Operation and support engineering systems
Satellite operations
Satellite In-orbit maintenance
Power station operations
Ground station maintenance
Complete lifecycle engineering systems
Satellite manufacture
Spacelift
In-orbit assembly
Transit to geostationary orbit
Satellite decommission
Rectenna manufacture
Power facility construction
Control station construction
Ground station decommission
Other controls and enablers
Legislation
Licenses
Standards
Permits
Environmental permits
International agreements
Planning consent

2.2. Space Based Solar Power overview

A typical system comprises four main elements:

- The solar power satellite (SPS);
- Space launch and transportation to orbit;
- Ground antenna including pilot beam and grid interface;
- Power and satellite mission control.

The Solar Power Satellite is a massive, kilometre scale spacecraft, typically in Geostationary Earth Orbit (GEO). It features large lightweight solar panels generating over 3 Gigawatts (GW) of electricity on the satellite. This is converted into high frequency radio waves and beamed to a rectifying antenna (rectenna) on the earth. This is termed 'wireless power transmission (WPT)', and the radio frequency proposed is in the 1 – 10GHz 'atmospheric window', making it capable of beaming at full power irrespective of the seasons and weather.

An encrypted pilot beam sent from the ground to the satellite ensures both security and control of the transmitted energy. The rectenna converts the radio waves into electricity and typically around 2GW of power is delivered into the grid. Each SPS is thus comparable in power output to a nuclear power station.

Although very large, the satellite construction is quite different from a traditional spacecraft. It is highly modular, comprising a handful of solid state module types, and using a very large number of each type of module. The modules can therefore be mass-manufactured, driving the production cost down dramatically. This modular approach also provides good resilience and redundancy in the event of damage or technical faults, as there are no single points of failure. The modules are designed for assembly by autonomous robots in orbit, minimising the need for human spaceflight. All these features keep the cost of production and operation low, and result in the system offering a competitive Levelised Cost Of Electricity.

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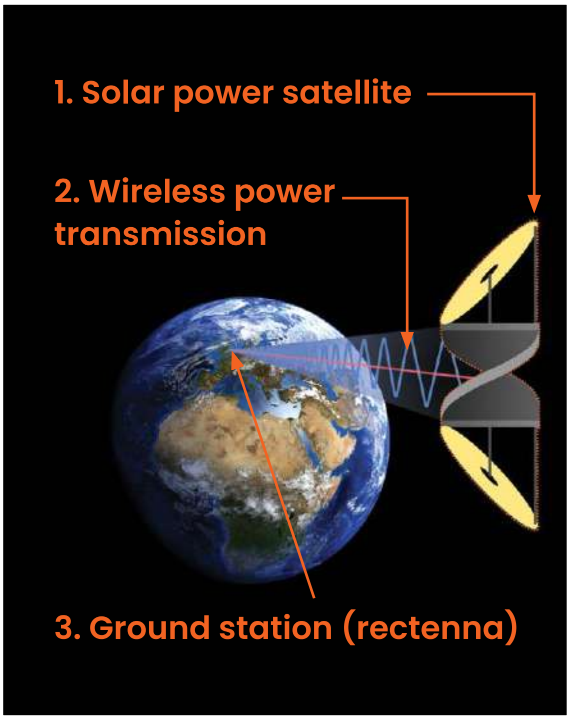

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Earth image: iStock.com/MarcelC

1. Solar power satellite

Collecting solar power and transmitting down on Earth

- 2,000 tonnes
- 1,700m diameter
- Geosynchronous Orbit - 35,786km

CASSIOPeiA Solar Power Satellite concept (International Electric)

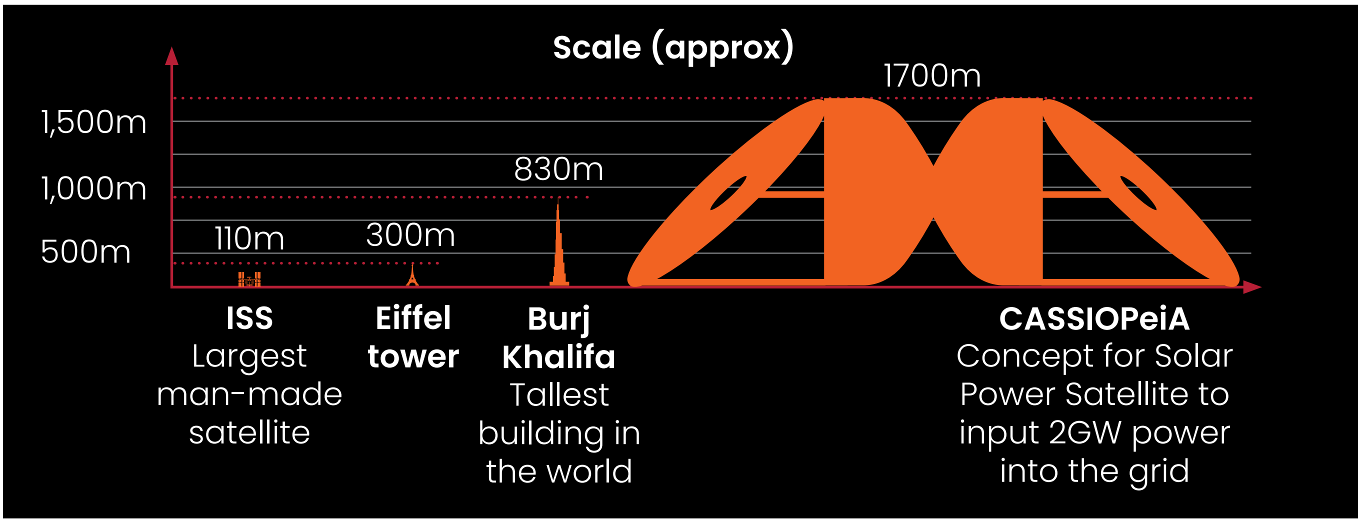
2. Wireless power transmission

High frequency radio wave transmission from satellite to receiver on ground (ground station)

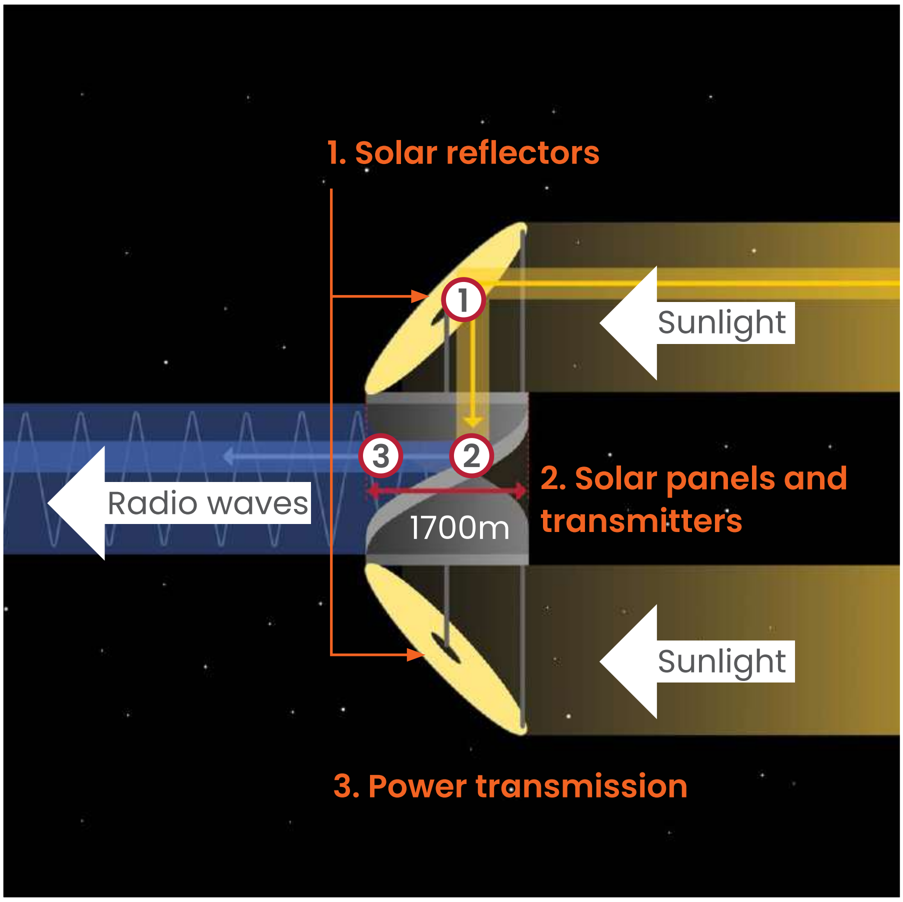
- Specific frequency (e.g. 2.45GHz)
- Locked onto pilot beam from ground station

3. Ground station (rectenna)

- 6.7km by 13km elliptical rectenna
- Receiving 245W/m² high frequency radio wave power
- Generating 2GW into grid



Solar Power Satellite - Overview



1. Solar reflectors
Orientation of satellite with respect to the sun, controlled to constantly reflect sunlight onto the solar panel array below.

2. Solar panels and transmitters
~60,000 layers of solar panels that collect the sunlight from the reflectors, and convert this to transmit high frequency radio waves.

3. Power transmission
Direction of radio wave 'beam' controlled through changing phase of waves (beam combined from all layers).

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2.3. Ground system elements

The ground infrastructure comprises the power and satellite mission control, and the rectenna. The latter is physically a large open net structure, holding the small dipoles, or aerials which capture the radio wave energy and convert it to DC electricity. The maximum beam intensity at the centre of the rectenna is limited to around 240W/m^2, or about a quarter of the intensity of the sun at the equator. Thus the system is inherently safe for life on earth.

The rectenna is typically an elliptical shape at UK latitudes, measuring about 6.7km x 13km. To put this in context, this represents a power density of about 29W/m^2, requiring one third of the area compared to the equivalent terrestrial solar power. Terrestrial solar in the UK has an average power density of just 10W/m^2, including diurnal and weather factors. One possibility is to co-locate the rectennae offshore with existing wind farms, and connect them into the existing grid connections.

2.4. Space transportation and infrastructure

Launching the thousands of tonnes of satellite hardware from Earth to orbit is a dominant cost factor for Space Based Solar Power. Over the last decade space launch costs have fallen dramatically, with new commercial entrants such as SpaceX and Blue Origin developing reusable vertical launch rockets. These trends are set to continue further, and the large market demand for space launch created by Space Based Solar Power is likely to accelerate the drive to develop even more affordable and fully reusable spaceplanes.

Assembly of the satellite modules would be carried out by autonomous robots in Medium Earth Orbit (MEO) to avoid the risk from space debris in Low Earth Orbit (LEO), and above the harsh radiation environment of the inner Van Allen belt. The assembled satellite would then be raised up to GEO using very efficient solar electric propulsion, powered by the solar power satellite itself.

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global solution

Solving the world's clean energy need

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3

Is it feasible?

3.1. Engineering feasibility

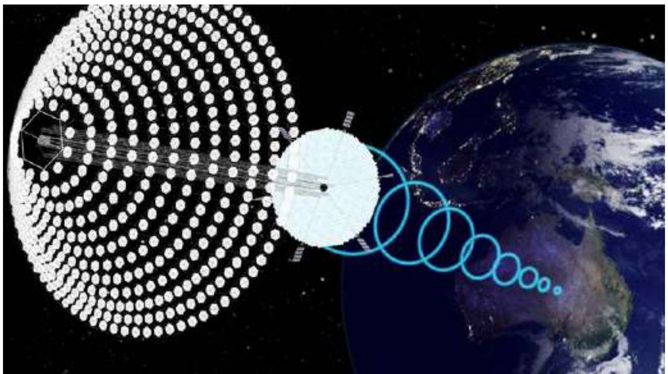
Our study[2] has shown that it is technically feasible to develop a substantial Space Based Solar Power capability for the UK, and to complete this well before 2050.

Two leading baseload Solar Power Satellite (SPS) designs are the SPS Alpha (designed by John Mankins, USA) and CASSIOPeiA (designed by Ian Cash, UK). Whilst our cost modelling has focussed on CASSIOPeiA, we conclude that both these designs are technically and economically viable.

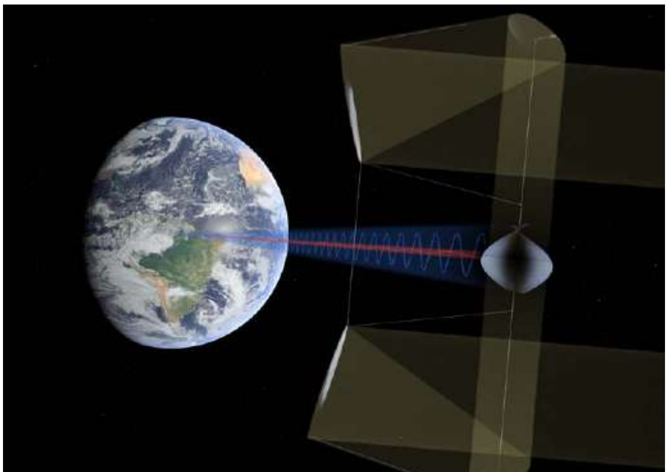
> ***The leading baseload Solar Power Satellite concepts offer credible and competitive solutions for the UK.***

The leading SPS concepts do not require any substantial advance in materials' technology or performance. However to build them economically will require two principal capabilities which are today immature but rapidly developing: robotic in-orbit assembly, and a low cost reusable space transportation infrastructure.

The current Space Based Solar Power system maturity is low, and given the scale and ambition of this system, there is considerable engineering risk which can be addressed and mitigated by a programme of design and technology demonstration.



SPS Alpha



CASSIOPeiA

[2] Frazer-Nash Consultancy Phase 1 Report ref 004456-51057R

3.2. What are the risks?

Development of Space Based Solar Power would be a substantial undertaking, primarily because of the size of the system, and the need to assemble and integrate this in space. The solar power satellite would be an order of magnitude larger in mass and extent than any spacecraft currently in orbit.

One of the major considerations is achieving the necessary performance in terms of its power to mass ratio (kW/kg). This requires a low system mass, and demonstration of efficient power transfer through the energy chain from the solar photovoltaic panels in space, to the electricity grid. The SPS Alpha and CASSIOPeiA concepts studied have assumed realistic efficiency values and power to mass ratio for the sub-systems, and we have identified independent evidence from technical literature supporting these claims. The overall power to mass ratio is around 0.5 - 1.0 kW/kg, which is considered ambitious but feasible given a development programme.

0% NET ZERO

Space Based Solar Power could provide new options for delivery of Net Zero, and its characteristics align well with the BEIS criteria for a new energy technology.

“Development and demonstration is required to answer key questions.”

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The key risks and considerations are summarised below:

Political

- Integration with energy policy
- Land use - rectenna sites
- Development timescales
- Integration with national infrastructure
- Responsibility and security of operations
- International collaboration

Technological

- In-orbit robotic assembly, maintenance
- Lightweight sandwich panel modules
- Size and scale of satellite
- Wireless power transmission efficiency
- Accurate energy beam pointing and control
- Operational life in space environment

Economic

- LCOE vs other renewable tech
- Development funding / long ROI
- Economics of space launch
- Industrial capability

Legal

- Development of regulations
- ITU spectrum allocation for WPT
- Orbit allocation for satellite

Social

- Public acceptance of technology
- Demonstration and acceptance of safety

Environmental and safety

- Rectenna site environmental impact
- Through life carbon / sustainability
- Proving long term operational safety
- Decommissioning strategy / orbital debris

3.3. Why is it becoming feasible now?

Long seen as an attractive but unaffordable source of clean energy, the proponents of Space Based Solar Power suggest that over the last decade it has become both technically feasible and economically viable.

There are several reasons behind this renewed global interest in Space Based Solar Power:

- **Net Zero:** Both the urgency and technical challenges of decarbonising economies are driving nations to look at new technologies;
- **Commercial space launch:** The cost of space launch has fallen dramatically in recent years and this trend is set to continue;
- **Modular satellite designs:** New highly modular solid state solar power satellite designs such as SPS Alpha and CASSIOPeiA have been conceived which are designed for high volume commercial manufacture, and are thus far more affordable than previous concepts;
- **Technologies maturing:** The underpinning technologies of high concentration solar photovoltaic panels, wireless power transmission and space robotics are rapidly maturing;
- **Strategic self-interest:** Other nations may see strategic advantage and global influence in being able to develop a source of abundant affordable energy which could potentially be beamed anywhere in the world.

3.4. Why should we pursue this now?

Our development roadmap identifies a number of demonstration steps, and concludes that it is feasible to realise a constellation of solar power satellites delivering a substantial percentage of the UK's energy needs by the early 2040s.

Assuming a start at the end of this year, the main development and demonstration steps and timescales are shown on the next page, with a description of the main outcomes at the end of each phase.

With the urgency to decarbonise our economies by 2050, and given a lengthy development and production timeframe, we recommend that development starts soon to secure the benefits of this technology as quickly as practical. This keeps the option for this technology open to energy policy makers whilst the technology is maturing, and de-risks the pathway to Net Zero, for a comparatively small investment in the early years.

Image credit Reaction Engines Ltd.

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2022 – 26
PHASE 1
Ground based satellite demonstrator and balloon trials

Phase 1
- WPT performance parameters established
- Rectenna design established
- SPS architecture confirmed
- Energy chain conversion efficiency confirmed

2027 – 31
PHASE 2
40MW SPS demonstrator in low earth orbit

Phase 2
- Meaningful power transmitted from orbit to earth
- Viability of SPS established
- SPS module sizes and configurations established
- Atmospheric effects on WPT investigated
- Assembly robots designed

2032 – 35
PHASE 3
500MW SPS demonstrator in operational orbit

Phase 3
- Autonomous in-orbit assembly demonstrated
- Packaging for space lift optimised
- Reflector and structure optimised
- SPS and WPT control optimised
- SPS available for commercial power at end of tests

2036 – 39
PHASE 4
2GW SPS Production prototype in operational orbit

Phase 4
- Full scale demonstration of the operational system
- Industrialisation of SPS manufacture complete
- Space launch capacity and providers in place
- SPS available for grid connection at end of tests

2039 – 42
Production and operation delivering 15% of UK energy

> ***“Space Based Solar Power could deliver a substantial part of our energy needs by 2042.”***

3.5. International efforts

Several nations have Space Based Solar Power system concepts and technology development programmes, as summarised below. National policy-led programmes of scale exist in the USA, China and Japan, and there is strong interest in collaboration with the UK from our natural partners. International technical discussion of activities is currently coordinated via the International Astronautical Federation (IAF) Space Power Committee, and there is genuine and strong appetite for collaboration from all parties, across boundaries.

There is scope for the UK to take a political leadership role, which could be fully open, or focussed on strategic international partners.

Country/ Region	Overview of Space Based Solar Power development and government support
USA	The USA is pursuing substantial defence research, with a $180 million programme led by Northrop Grumman and the US Air Force Research Lab (AFRL) to develop and demonstrate technology including lightweight sandwich panel PV / RF modules, and lightweight extendable mirrors, under the SSPIDR (Space Solar Power Incremental Development and Research) Project. Separately, the Naval Research Lab (NRL) is conducting power collection and conversion experiments in space on the X-37B spaceplane. There is currently no civil energy policy from the US Department of Energy related to Space Based Solar Power.
Japan	Since the 1980s Japan has undertaken well-funded research into Space Based Solar Power, primarily focussing on WPT, and including in-space experiments. Japan has established space solar power as a national goal enshrined in its Basic Space Law, and JAXA (Japan Aerospace Exploitation Agency) has a roadmap to commercial Space Based Solar Power. JAXA successfully demonstrated kW scale wireless power transmission in 2015.

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Country/ Region	Overview of Space Based Solar Power development and government support
China	The China Academy for Space Technology (CAST) has a declared Space Based Solar Power programme and presented a roadmap at the NSS International Space Development Conference in 2015. The Chongqing Collaborative Innovation Research Institute for Civil-Military Integration in China is constructing a facility for Space Based Solar Power testing. A number of power beaming experiments are being pursued. In March 2021, a new Committee of Space Solar Power was established, to be chaired by Professor Ming Li.
South Korea	A number of power beaming activities are being pursued by KERI (Korea Electrotechnology Research Institute) and private organisations.
Europe	ESA (European Space Agency) has periodically conducted studies on Space Based Solar Power over the last two decades. Recently ESA issued a small scale call for ideas to research technologies related to Space Based Solar Power.
Canada	There is interest at ministerial level but no government supported activities.
Australia	There is interest within the Australian Space Agency and at ministerial level, but no published government supported activities.

sustainable

Inspiring the next generation

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4

Why should the UK pursue Space Based Solar Power?

4.1. Alignment with UK strategic priorities

If other countries are pursuing Space Based Solar Power, should the UK take a leading role in developing this technology?

A UK development programme could be strongly aligned with UK strategic priorities, most notably the imperative to deliver Net Zero:

UK global position
- High profile infrastructure programme
- Global societal benefit
- Cutting edge technology, UK leadership
- International collaboration

Economic prosperity
- Competitive LCOE - affordable energy
- Economic benefit from development
- Wider spin-off benefits
- Export potential

Net Zero
- Make a substantial contribution by 2042
- De-risks the Net Zero energy pathways
- Integrates well into future energy mix
- Sustainable, zero waste

Growing space capability
- Supports goal - 10% of global space market
- Ability to operate routinely in space domain
- Key technologies - robotics, PV, WPT
- Industry, academia and regulatory expertise

Security of critical infrastructure
- Sovereign control (freedom of action)
- Reliability / dependability
- Resilience to disaster / terrorism
- Sustainability / availability of fuel

Industrial strategy
- Levelling up agenda and regional support
- Establish brand new industry / market
- Create high value skilled jobs
- Inspiring the next generation - STEM

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4.2. International collaboration?

The successful development of Space Based Solar Power will require a very substantial research and development programme, with a sustained effort over the next two decades and commitment by government until the technology is sufficiently mature for private financing. International collaboration could help to share the burden of risk and funding, whilst aligning with UK objectives to be a global partner.

During the study we have held exploratory discussions with John Mankins on the American and Australian Space Based Solar Power initiatives, and we have met with the Japanese Space Based Solar Power community including Ministry of Economy, Trade and Industry (METI), JAXA and Japan Space Systems.

There may be an appetite for a collaboration with our natural partners, including Europe, members of the Five Eyes intelligence alliance, and Japan, for a civil Space Based Solar Power development programme.

4.3. Levelised Cost of Electricity

We have developed a cost model of Space Based Solar Power for the UK, comprising five 2GW grid connected power stations, and based on the CASSIOPeiA concept. It provides estimated values for the Levelised Cost of Electricity (LCOE), including the end to end production, launch, assembly, operational service life and decommissioning. The model uses an analysis technique which is ideal for treatment of cost metrics where there is considerable uncertainty.

It is consistent with the BEIS methodology, meaning that the LCOE values can be directly compared with other renewable energy LCOE figures.

The estimated value of LCOE is £50/MWh, with an investment hurdle rate of 20%, and assuming the system is commissioned in 2040. This very high hurdle rate, in comparison with other renewable technologies, was chosen to reflect the present low maturity of Space Based Solar Power. However as the technology matures through the course of a development programme, it would be appropriate to apply a lower hurdle rate, thus reducing the LCOE.

> *Space Based Solar Power could thus command strong market demand, making it attractive to investors.*

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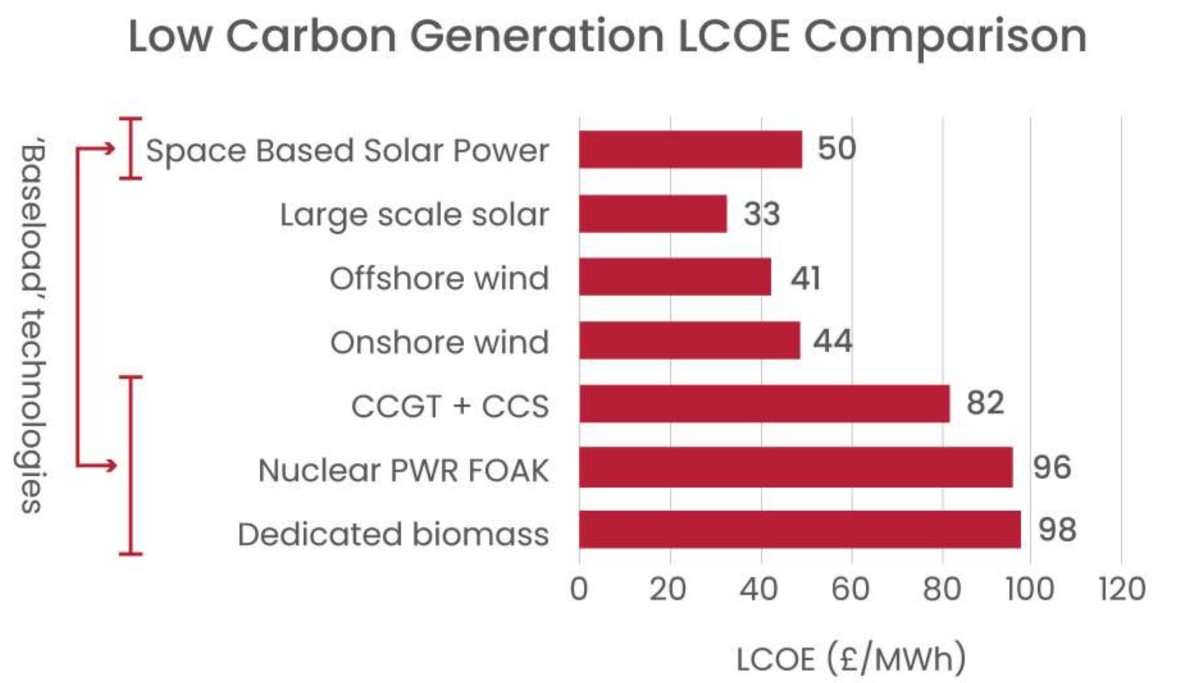
This LCOE is compared with BEIS projections for other renewable technologies commissioned in 2040[3]: Baseload energy is essential for grid stability, and in comparison to Combined Cycle Gas Turbine plus Carbon Capture and Storage (CCGT + CCS), Nuclear and Biomass, it is very competitive with these other baseload generation technologies. Space Based Solar Power could thus command strong market demand, making it attractive to investors.

4.4. Reducing risk for the Net Zero pathways

To date none of the Net Zero pathways have considered Space Based Solar Power. From the work done in this study, the positive findings on its technical feasibility and comparable LCOE with other generation technologies, we recommend that energy scenario modelling is conducted to further quantify how Space Based Solar Power could de-risk the pathways to Net Zero.



LCOE (NOAK) vs other low carbon energy generation

LCOE for Plant comissioned in 2040, using technology specific hurdle rates, NOAK (unless specified) 2018 prices. Comparison data taken from Electricity Generation Costs 2020 Report.

NOAK - 'N' of a Kind
FOAK - First of a Kind

[3] BEIS - Electricity Generation Costs 2020

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4.5. What would the government need to fund?

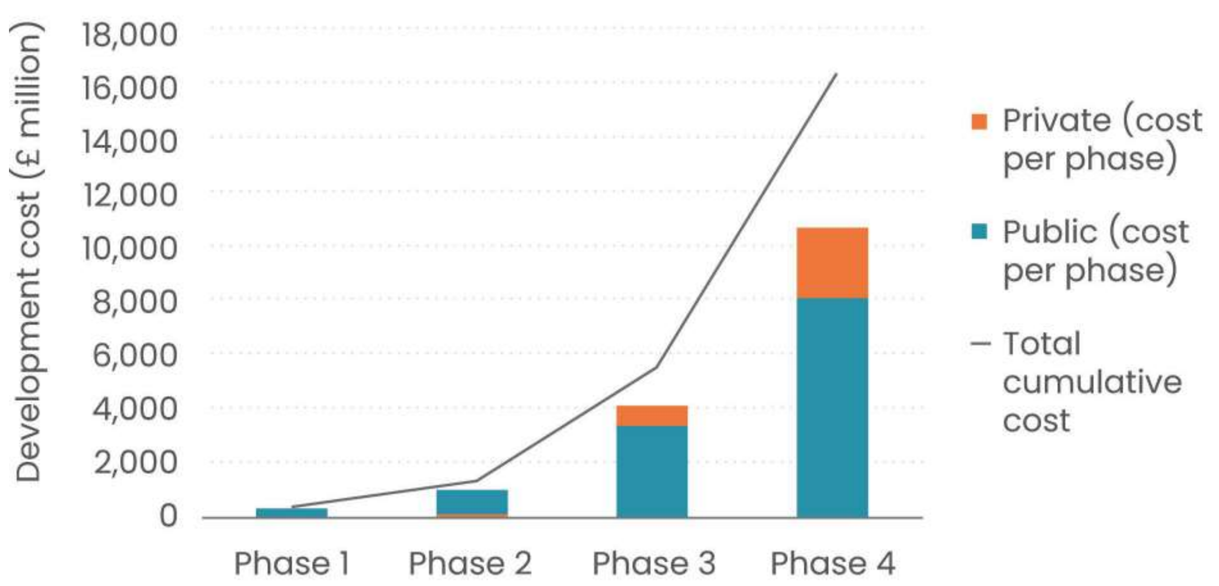
The Net Present Value (NPV) of overall development costs, including optimism bias, is estimated at £16.3 billion. Public sector funding will be needed to mature the technology to a point where the private sector is prepared to invest in Space Based Solar Power. This is due to the low technical maturity, the significant development costs and the fact that the financial returns occur only after many years of investment. Our analysis suggests that the public sector would need to fully fund Phase 1, totalling £350 million over the first five years. Thereafter the private sector could reasonably be expected to start investing an increasing proportion as shown.

4.6. Economic impact of the development

A public sector investment in such an infrastructure programme can be expected to support a significant economic footprint. A 'GDP multiplier' of 2.3 is estimated, reflecting the highly productive industries involved in the development and manufacture of this technology. This indicates that for every £1.00 of direct GDP, an additional £1.30 of indirect and induced GDP is supported.

The benefit cost ratio provides a measure of the likely scale of economic impact resulting from public sector investment. For this programme, the ratio is calculated to be 1.8, thus for every £1 of public funds spent to develop the first of a kind system, a further £1.80 is supported in the UK economy over the life of the programme.

The total programme cost up to 2040 for the 'first of a kind' Space Based Solar Power system, is £17.3 billion in present value terms, comprising the £16.3 billion development cost and £1.0 billion operating expenditure over the life of the system.



Development cost - NPV, including optimism bias

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4.7. Spillover benefits

A development programme will provide broader spillover economic benefits for the UK. These are in areas such as:

1. **Wireless power transmission**
   The ability to transmit useful power over significant distances without the need for cables is likely to have utility in a number of markets such as consumer electronics and electric vehicle charging. The development of high power microwave devices will benefit electric switching in power networks and better radar devices.
2. **Semiconductor technology**
   Improvements in high efficiency power electronics leading to high volume, low cost manufacturing processes will benefit a number of electrical power applications.
3. **Photovoltaic technology**
   Improvements in HCPV and the associated semiconductor technologies will benefit other space applications and specialist terrestrial solar collectors.
4. **Inspiring the next generation of students**
   This ambitious and exciting programme could inspire a generation of young people to pursue a career in engineering. It will encompass a wide range of STEM (science, technology, engineering and mathematics) topics.
5. **Market drivers for mass manufacture of space grade electronics**
   To support the increasing commercialisation of space.
6. **International energy trade via power beaming**
   Space Based Solar Power has the ability to deliver power to a wide range of locations, opening up the possibility of international collaboration for shared energy generation and support to provision of energy to remote geographic areas.
7. **Highly modular construction for robotic assembly**
   The continual drive to reduce manufacturing costs leads to an impetus for robotic assembly and thus products to be configured for this approach.
8. **Market drivers for low cost reusable space freight transportation**
   The market opportunity to encourage space freight companies to establish a commercial service.
9. **Autonomous robotic assembly in challenging environments**
   The ability to perform autonomous remote operations overcomes significant safety hazards when operating in challenging environments such as nuclear, chemical, offshore and subsea as well as in space.
10. **UK centre of excellence for space operations**
   To support the increasing commercialisation of space.

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5

Conclusions and recommendations

5.1. High level findings

The analysis presented in this study has found that:

- Space Based Solar Power is technically feasible, and could be developed by 2040;
- It offers a new source of economically competitive baseload electricity;
- It requires a £16.3 billion development programme that could be achieved within 18 years;
- Public funding would be required for the majority of the development, given the substantial risk, cost and timescales;
- There are broader economic benefits for the UK to pursue the development of Space Based Solar Power, with a favourable GDP multiplier and benefit-cost ratio. In addition development could lead to substantial spillover benefits;
- Development of Space Based Solar Power aligns well with a range of UK Government priorities;
- There are opportunities for international collaboration with our natural partners, and the UK is well placed to take a leadership role.

5.2. Recommendations

The main recommendations are grouped in five areas:

5.2.1. Policy and strategy

» Use existing energy models to quantify the contribution that Space Based Solar Power could make to the UK energy mix;

» Integrate Space Based Solar Power across relevant Government strategy and policies, including Net Zero; National Space Strategy; Innovation Strategy.

5.2.2. UK Research and development

» Conduct concept design studies and develop the engineering requirements for a UK system;

» Examine the political, societal, legal and environmental considerations;

» Establish a multi-year programme of technology development;

» Establish the industrial and technology priorities for the UK, to help position for international discussions.

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5.2.3. Energy market engagement

- Engage further with the energy generation and distribution companies as key future stakeholders;
- Maintain a technology watch on the development of other renewable energy options.

5.2.4. Space transportation

- Conduct regular analysis of international market trends and capabilities to inform strategic decisions on procuring space lift;
- Establish UK strategy for collaborative development or procurement of fully reusable heavy lift capability;
- Together with European partners, explore the business case and development path for the UK's SABRE air breathing engine technology as a core component of a future European fully reusable heavy lift launch system.

5.2.5. International collaboration

- Consider profiling Space Based Solar Power at the COP26 conference in November 2021;
- Given a clear view on UK R&D priorities, initiate international discussions with our natural partners to explore collaboration on a development programme.

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6

Summary

The study concludes that Space Based Solar Power is technically feasible, economically competitive and well aligned with UK Government priorities.

It offers new options to de-risk the pathways to Net Zero. A number of challenges and considerations are identified which can be answered with a staged programme of development and demonstration. The associated costs and economic benefits are identified. Recommendations are made that the UK should integrate Space Based Solar Power into key Government policies, and take a leadership role in developing the technology.

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