UK Government

RAF036/2425: Feasibility of Small-Scale Space Based Solar Power (SBSP) Systems for Early Market Adoption

Final report

Frazer-Nash Consultancy, Space Solar Engineering Ltd & Imperial College London (2025)

Acknowledgements

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Executive summary

Small-scale SBSP's role in supporting a pathway to Net Zero

Current forecasts by the National Energy System Operator (NESO) suggest that peak electricity demand will more than double from 58 gigawatts (GW) in 2025 to 119 GW in 2050.[1] To meet Net Zero objectives, the UK must maintain the affordability of transmission and distribution networks, while significantly increasing renewable power on the GB network. Previous studies have suggested that space-based solar power (SBSP) could provide GB with constant, predictable, zero-carbon power at the GW scale.[2] However, without prior de-risking, the scale of the upfront investment required for the first large-scale system may deter investors, making it more difficult to unlock the full benefits of SBSP.

The Department for Energy Security and Net Zero (DESNZ) commissioned Frazer-Nash Consultancy (Frazer-Nash) to assess the economic and technical feasibility of deploying a smaller-scale SBSP system. This would have a much lower upfront cost, potentially allowing faster commercialisation and unlocking the benefits of SBSP earlier while also de-risking the later implementation of a large-scale system. This report presents the study's findings, including definition of a minimum viable product (MVP), identification of small-scale SBSP's benefits and potential markets for the energy, and an assessment of economic viability.

Summary of findings

- **The small-scale reference design is efficient.** The small-scale SBSP reference design faces similar technical constraints to larger designs and, despite being smaller, compares favourably to these in terms of both total efficiency and specific power (0.58kW/kg), which is an important determinant of economic feasibility.
- **Small-scale SBSP is most effective in a highly elliptical orbit (HEO)**. The orbit selected for this study—a HEO with a perigee of 556 km and an apogee of 7,821 km—is superior to a circular low Earth orbit (LEO) for a sufficiently high energy price.
- **Small-scale SBSP can provide baseload power that displaces both intermittent renewables and fossil fuel generation.** Small-scale SPSP in HEO is capable of providing 95.7% utilisation to the UK on average throughout the year. Small batteries at the rectenna could smooth out interruptions to allow constant power.
- **Small-scale SBSP can also be configured to provide high value dawn/dusk power.** A constellation could instead be configured to provide double the instantaneous power and specifically between dawn and dusk, albeit at a lower utilisation and with additional rectenna costs to capture this power.
- **Compared to other low-carbon technologies, small-scale SBSP has several benefits.** It provides reliable all-weather generation, can deliver export revenues without

[1] NESO Future Energy Scenarios 2024: Electric Engagement Peak Demand. Available here: FES Documents
[2] Frazer-Nash report for UK government shows feasibility of space solar power | Frazer-Nash Consultancy; Study on Cost-Benefit Analysis of Space-Based Solar Power (SBSP) Generation for Terrestrial Energy Needs

needing physical transmission assets, can offer locational flexibility to ease GB grid costs and is likely to generate technological spillovers.

- **The introduction of small-scale SBSP is likely to contribute to the economic feasibility of large-scale SBSP systems.** Small-scale SBSP's technological development directly improves the performance, cost and risk profile of a large-scale system. It is likely to reduce large-scale SBSP's first of a kind (FOAK) hurdle rate, contributing to LCOE reductions between 16% and 27%.
- **Opportunities for small-scale SBSP in the ancillary services market seem limited.**
- **There is a significant global market for small-scale SBSP.** In some markets, notably polar research bases, there is evidence that small-scale SBSP could undercut current energy generation methods in terms of both price and carbon emissions.
- **The LCOE of a FOAK small-scale SBSP implementation in 2030 is expected to be between £335/MWh and £595/MWh, delivering 585 GWh a year. It is expected to fall to between £154/MWh and £249/MWh by 2035 (delivering 790 GWh a year) and between £87/MWh and £129/MWh in 2040 (representing nth of a kind and delivering 980 GWh a year).** Adjusting for energy system benefits reduces these estimates by £21/MWh in all cases.
- **Launch is the most significant cost driver, accounting for more than 50% of the variance in LCOE.** The influence of launch cost grows throughout the 2030s as the satellite build cost becomes less significant, driven by learning and economies of scale.
- **In present value terms, energy system benefits associated with small-scale SBSP are expected to be £13.6 million per year in 2030, £18.4 million per year in 2035 and £22.8 million per year in 2040 (NOAK).** The energy system benefits depend largely on rectenna location. A rectenna in the south of England provides significantly more benefit than a rectenna in Scotland due to grid constraints.
- **A FOAK small-scale SBSP system requires significant public and private support; the level of support required falls quickly throughout the 2030s as system costs and hurdle rates fall and performance increases.**

Conclusion

The study concludes that, while costs are initially high, the right investment and support now could enable small-scale SBSP to become an economically competitive source of power by 2040. Small-scale SBSP has the potential to support a pathway to Net Zero by de-risking the pathway to a large-scale system, thereby reducing barriers to investment.

To further develop the case for small-scale SBSP, both public and private sector support will be needed to help industry resolve and overcome technical barriers.

Contents

1. Introduction

The Department for Energy Security and Net Zero (DESNZ) commissioned Frazer-Nash Consultancy (Frazer-Nash) to assess the economic and technical feasibility of deploying small-scale space-based solar power (SBSP) in the 2030s to support a pathway to Net Zero. Frazer-Nash have partnered with Space Solar Ltd and Imperial College London to deliver the study. London Economics Ltd have provided independent peer review.

This report presents the findings of the study. It defines the technical specifications of a minimum viable product (MVP) system, including performance, orbit and the properties that separate small-scale SBSP from other low-carbon technologies. The report analyses the future serviceable market and assesses the extent to which small-scale SBSP is compatible with the contracts for difference (CfD) mechanism, accounting for levelised cost of electricity (LCOE), energy system benefits and supplementary funding options.

Background and context

The UK government's plan to reach Net Zero carbon emissions by 2050 relies on the electrification of several sectors including manufacturing, housing and transport, which will rapidly increase electricity demand. Current forecasts by the National Energy System Operator (NESO) suggest that peak electricity demand will more than double from 58 gigawatts (GW) in 2025 to 119 GW in 2050.[3] Meeting Net Zero objectives requires maintaining the affordability of transmission and distribution networks, while significantly increasing renewable power on the GB network. This brings significant challenges, both for the infrastructure needed to deliver the energy from generator to user, and for reliability of supply, since the existing major source of renewable energy in the UK—offshore wind—is weather dependent and intermittent. When intermittent renewables are unavailable, high carbon and high-cost fossil fuel generation replaces them, contributing significantly to energy system costs.

Previous studies have investigated whether SBSP could provide GB with constant, predictable, zero-carbon power at the GW scale.[4] These studies identified significant potential for SBSP to deliver competitive baseload generation. Frazer-Nash's 2021 economic feasibility study identified the upfront cost of a first of a kind (FOAK) large-scale (2 GW) SBSP system as £10.2 billion,[5] which translates to a competitive expected central LCOE of £62/MWh.[6] However, without prior de-risking, the scale of the upfront investment required for the first large-scale system may deter investors, making it more difficult to unlock the full benefits of SBSP. This study explores the viability of a smaller-scale SBSP system that could provide megawatt (MW)-scale power at much lower upfront cost. This smaller system could be commercialised more

[3] NESO Future Energy Scenarios 2024: Electric Engagement Peak Demand. Available here: FES Documents
[4] Frazer-Nash report for UK government shows feasibility of space solar power | Frazer-Nash Consultancy; Study on Cost-Benefit Analysis of Space-Based Solar Power (SBSP) Generation for Terrestrial Energy Needs
[5] Since 2021 Space Solar has undertaken further development work. The first system in geostationary orbit is now likely to be smaller, providing 650 MW of power and with a significantly smaller initial capital cost.
[6] Value adjusted to 2024 GBP using ONS CPIH

quickly, unlocking the benefits of SBSP earlier and de-risking the later implementation of a large-scale system.

Scope and objectives

This study sets out to understand the viability of a smaller-scale, proof of-concept SBSP system that could be deployed by the 2030s, which would both de-risk investment into larger-scale SBSP and demonstrate a pilot system. It aims to understand how a minimum viable product (MVP) system should be sized and configured to maximise both the utility to the GB electricity grid and provide indicative revenues achievable for investors. It assesses the commercial feasibility of an optimised system, providing insight into how quickly small-scale SBSP can be operational and the extent to which it can support the pathway to Net Zero. The study provides:

- Independent and evidence-based determination of minimum viable *performance*, and the minimum viable *product* (MVP) that could deliver this.
- Robust development of whole-lifecycle costs using reliable data from industry sources.
- Meaningful insight into the MVP's impact, including how it could affect the GB energy system and its economic impacts by considering quantitative benefits and market opportunities.
- Confidence that the MVP is scalable from 2030, and the returns are attractive to private investors.

Study limitations

- **The economic and technical viability of a FOAK small-scale system is dependent on highly uncertain future outcomes.** The study bases its prediction for the future state of the GB energy market on the electric engagement future energy scenario.[3] If the GB energy market deviates significantly from this prediction, then some of the study's findings (particularly the energy systems benefits results) lose validity. Moreover, the analysis depends on uncertain and externally determined factors. For example, launch costs depend on the assumed capability of SpaceX's Starship. Sensitivity analysis is conducted to explore the impact of different future outcomes on results.
- **The continued progress of small-scale SBSP in the 2030s relies on a strong and continuous demand signal.** If this demand signal is not present, then there will be insufficient incentive for providers of small-scale SBSP solutions to invest in technical development and the forecast improvements in performance will not materialise.
- **The technical specifications of the small-scale SBSP reference design are not yet sufficiently mature to facilitate a full bottom-up cost estimate.** Rather, the study relies on costs provided by Space Solar (themselves derived from the 2021 Frazer-Nash study), which are independently reviewed and compared to values in published

literature where possible, with optimism bias adjustments applied in some cases. Full details are provided in Annex A.

- **LCOE is an imperfect measure of economic viability.** LCOE does not capture the system costs of variable renewable energy. This limitation is discussed ahead of the LCOE methodology in Annex A.
- **Simplifying assumptions are made where quantitative calculation is highly complex or uses highly uncertain parameters.** These assumptions are flagged ahead of relevant calculations or in technical annexes.

Report structure

The report is structured as follows:

1. Chapter 1—this introduction—provides an overview of the study scope and objectives and sets out the background and context.
2. Chapter 2 compares current SBSP designs and justifies the reference design that is taken forward as the 2030 MVP.
3. Chapter 3 elaborates on the parameters that define the scope of the analysis, including the counterfactual and two potential constellation set-ups.
4. Chapter 4 explores the unique properties of small-scale SBSP compared to other low-carbon technologies and places small-scale SBSP in the context of the wider SBSP development roadmap.
5. Chapter 5 summarises the market for small-scale SBSP, including GB-grid and global market opportunities.
6. Chapter 6 assesses affordability under the contracts for difference mechanism, accounting for LCOE, energy system benefits and supplementary funding.
7. Chapter 7 concludes the study findings.
8. Annex A provides a detailed account of the LCOE estimation methodology, including justification of significant input values and sensitivity analysis.
9. Annex B lays out the full ancillary market review.
10. Annex C presents the global market analysis in full.
11. Annex D elaborates on the energy system benefits modelling approach.

2. SBSP systems

This section introduces SBSP and compares existing SBSP designs. It defines the criteria that a 2030 small-scale minimum viable product (MVP) must meet and identifies the MVP that is used as the reference design in this study.

An SBSP system involves one or multiple satellites equipped with lightweight solar panels capturing the sun's energy in space. The satellite generates electricity, converts it into microwave radiation (usually of frequency less than 10GHz to minimise atmospheric attenuation) and beams it to a ground-based rectifying antenna (rectenna). The rectenna converts the microwave energy into direct current electricity, which is then transformed to alternating current to deliver power, either to the grid or another application. SBSP systems can vary in size, satellite orbit and the power output, with the potential to form constellations that can contribute significantly to a nation's energy infrastructure.

This study compares a range of leading SBSP designs—small-scale and large-scale—to highlight similarities and differences and provide a comparison of key assumptions. The designs compared in this study include the following:

Large-scale systems

- **NASA Representative Design (RD)1** – A low technology readiness level (TRL) 'Innovative Heliostat Swarm' design, derived from the SPS-Alpha Mark III concept.[7]
- **NASA RD2** – A 'Planar Array' design, derived from the Sasaki Tethered-SPS concept.[7]
- **Thales Alenia Space (TAS) ESA** – The reference design of a pre-phase A system study produced by TAS for the European Space Agency (ESA), based broadly on NASA's 1980 solar power system.[7]
- **Space Solar large-scale** – A 650 MW large-scale system based on the CASSIOPeiA design, available from 2040.[7]

Small-scale systems

- **Virtus Solis Project #1** – A modular array assembling metre-scale 'tile' satellites.[7]
- **Space Solar small-scale** – A small-scale design based on CASSIOPeiA, delivering MW scale power from 2030.[7]

Table 1 presents a comparison of these systems, based on manufacturers' claimed values (not independently verified by Frazer-Nash). Missing values are inferred where possible. Technologies are presented at different maturities, in different orbits and at different sizes, and Table 1 is not an indication of which technologies should be preferred. Space Solar designs are presented for 2040, representing nth of a kind (NOAK) for both systems.[7]

[7] Sources include Space Based Solar Power, NASA (2024); Survey of Space Based Solar Power, Virtus Solis (2024); Space-Based Solar Power, Thales Alenia Space (2023); Space Solar.

Stage	Parameter	NASA RD1	NASA RD2	Thales Alenia Space ESA	Space Solar large-scale	Virtus Solis P1	Space Solar small-scale
	Orbit	GEO	GEO	GEO	GEO	HEO	HEO
	RF Frequency (GHz)	2.45	5.8	2.45	5.8	10	5.8
	Hurdle rate	-	-	15%	13.1% - 20%	13%	9.1% (20% FOAK)
Collect	Incident solar energy (MW)	15,700	26,000	8,500	3,550	1,000	350
	Solar cell efficiency	35%	35%	24%	37%	31%	37%
Convert in space	Total DC to RF and antenna emission efficiency	57%	57%	78%	69%	74%	69%
Transmit	Atmospheric travel efficiency	98%	98%	99%	98%	95%	98%
Receive	Rectenna diameter (km)	6.0	4.0	5.4	6.7	2.0	3.4
	Rectenna collection/reception efficiency	74%	74%	67%	77%	92%	64%
Convert and deliver	Conversion efficiency	90%	90%	94%	95%	99%	95%
	Peak power delivered (MW)	2035	3370	1,000	650	200	52
	Specific power (kW/kg)	0.33	0.20	0.15	0.67	0.27	0.58
	Total efficiency	13%	13%	11.7%	18.3%	19.9%	14.9%
	Capacity-adjusted efficiency	12.9%	7.8%	11.6%	18.2%	17.7%	14.1%

Note that large differences between parameter values may indicate differences in how these parameters are calculated/defined across manufacturers. For instance, the rectenna collection efficiency claimed by Virtus Solis would not be achievable under the calculation methodology used for other designs.[8]

The MVP reference design

A minimum viable product (MVP) must meet the following conditions:

- It must be **efficient** in capturing, transmitting and delivering power to the UK grid. This implies:
    - A high specific power (mass efficiency) – the power delivered to the ground per unit mass. This is important for economic feasibility because it impacts launch costs, which are a key component of total cost.
    - A high total efficiency - the average power delivered as a proportion of incident solar energy.
- It must be **aligned with the UK's decarbonisation and energy security objectives.** That is, it must provide low-carbon power that is capable of either:
    - Providing continuous or near-continuous baseload power as to enable electrification by increasing the UK's energy supply, or
    - Providing high-value power at times of peak energy demand, reducing the requirement for high cost, high emission fossil fuel power.
- It must be able to provide **economically competitive power** to the GB energy grid **between 2030 and 2040** and contribute to the economic viability of later large-scale SBSP systems**.**

This study takes forward Space Solar's small-scale system as a reference design and explores the extent to which it meets these conditions. The comparison in Table 1 shows that Space Solar's small-scale SBSP design is efficient. Its total efficiency is highly competitive and, more importantly, it has the highest specific power of any system, excluding Space Solar's large-scale design. A high specific power is highly important for economic viability, because launch costs are a significant portion of total cost. If a system has a high specific power, it incurs a smaller launch cost per unit of electricity generated, increasing economic viability. Space Solar's small-scale design therefore provides a suitable reference against which small-scale SBSP can be assessed. The remainder of this report focuses on this design's ability to provide baseload or high value power and assesses the extent to which this power is provided at an economically competitive cost.

[8] In particular, other designs assume that a rectenna only economically captures the first maximum of a beam. This places an upper bound on the efficiency of this stage at 84%.

3. Scope and scenarios

This section elaborates on the reference design, defining key parameters and four scenarios for the GB energy system in the 2030s with varying contribution from small-scale SBSP. It explores the design's capability to provide baseload power and high intensity peak power to the GB grid.

Scope of analysis

The analysis in this study is specific to the reference design chosen and is intended to represent a feasible commercial scenario for this design. Within the bounds of the chosen design, there remain several unconstrained parameters that have a large influence on economic feasibility. Four parameters have a significant influence on total system cost and energy production:

- Transmission beam frequency.
- Orbit choice.
- The number of satellites and rectennas.
- Launch strategy.

The following sections explore these parameters and justifies the specification analysed in this study.

Transmission beam frequency

The frequency at which energy is transported from space to the ground is determined by several factors:

- Physical factors such as atmospheric attenuation, which impact system efficiency.
- Practical factors, including industry conventions and regulatory limitations.
- Economic factors, including the cost, mass, and relative performance of power amplifiers.

Microwave frequency transmission possesses desirable properties for large power, large distance wireless transmission. Compared to visible and millimetre wave light, microwaves penetrate weather more effectively, enable more efficient conversion, are safer and much more economically viable at scale.[9]

This study considers the microwave frequency band between 1 and 100 GHz. Within this band, the impact of atmospheric attenuation is smallest in the 1 to 10 GHz range, particularly when there is heavy precipitation.[10] Between 1 and 10 GHz, atmospheric attenuation is between 0%

[9] Microwave and Millimetre Wave Power Beaming | IEEE Journals & Magazine | IEEE Xplore
[10] Attenuation by atmospheric gases

and 2%, depending on the weather. Thus, selecting a frequency in this range ensures high efficiency and reliable power transfer in all weather conditions.

The chosen frequency must be able to be implemented in a small-scale SBSP system by 2030, and as such it should conform to current regulations and be technically viable within that timescale. Within the 1 to 10 GHz range, there are two frequencies—2.45 GHz and 5.8 GHz—designated by the International Telecommunications Union (ITU) as ISM (industrial, scientific, medical) frequencies, which are unregulated. Thus, these two frequencies are considered to be viable options that could be implemented in a 2030 MVP solution. In the future, it is possible that the ITU will allocate a specific frequency to SBSP; in that case, the industry standard frequency for SBSP is at the ITU's discretion.[11]

Design analysis by Space Solar suggests transmission frequencies above 5.8 GHz are more technically difficult, requiring both smaller sized and tighter spacing of microwave components, antennas and the power core blades. As a result, current technologies above 5.8 GHz are less efficient, reducing feasibility within a 2030 MVP system.

All else equal, increasing the transmission frequency reduces the aperture size required to achieve a given power intensity on the ground.[12] Analysis by Space Solar suggests the optimum size for a 2.45 GHz system in GEO is 1,400 MW, and the optimum size for an equivalent 5.8 GHz system is 650 MW. The latter option is currently the anticipated specification for a first large-scale system. Therefore, applying the 5.8 GHz frequency to small-scale SBSP would most effectively de-risk and technically advance larger systems.

There is growing consensus for the use of 5.8 GHz across the SBSP market. It has been selected for several designs including Japan's Tethered SPS, SPS Alpha Mk IV, Space Solar's CASSIOPeiA and China's MMR SPS. The industry consensus, high efficiency and promising economic feasibility of the 5.8 GHz frequency means it is taken forward within the MVP design.

Orbit choice

The optimal choice of orbit is a trade-off between the cost of launch and transport to the destination orbit, and the operational utilisation rates of the system. Whilst geostationary orbit (GEO) is the favoured orbit for large-scale systems, it is unfeasible for small-scale SBSP. This is because smaller systems have a smaller beam aperture, which leads to significant diffraction from GEO. The result is a widely spread, low power intensity beam on the ground that is unfeasible to capture.

The optimal orbit, then, is a choice between various medium (between 2,000 km and 36,000 km) and low (less than 2,000km) Earth orbits. At low and medium Earth orbits, the time required for satellites to complete a rotation around Earth (the orbital period) is less than 24 hours, which means satellites in these orbits do not occupy fixed positions in the sky. Therefore, a single small-scale SBSP satellite in a low or medium Earth orbit cannot provide constant power to a fixed ground rectenna A high inclination orbit is required to service the UK,

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[11] Space Solar have held discussions with Ofcom and the ITU regarding frequency choices.
[12] REPORT ITU-R SM.2392-1 - Applications of wireless power transmission via radio frequency beam

so the orbit will precess, spending a significant amount of time not over a given fixed point (until it returns to the same ascending node). The closer the orbit is to Earth, the less total time it spends over the same fixed point on Earth, which results in the following trade off:

On one hand:

- Lower orbits require less thrust (Delta-V), making launch cheaper.

On the other hand:

- In lower orbits, satellites spend less time above a fixed point, reducing the amount of energy that can be collected by a rectenna.
- Satellites in lower orbits are subject to increased atmospheric drag and thus require more fuel to maintain the orbit over the same lifetime.

Two orbits were tested here for demonstration purposes.

1. A circular low Earth orbit (LEO) at 1,262 km with a period of 1 hour and 50 minutes.
2. A highly elliptical orbit (HEO) with a perigee of 556 km and an apogee of 7,821 km and a period of 3 hours.

Table 2 provides details of the two tested orbits.

Orbit option	Eccentricity	Argument of periapsis	Inclination
Circular LEO 1262 km	0	270°	100.7°
HEO 556 km x 7,821 km	0.344	270°	116.6°

Table 3 provides utilisation rates and approximated 2030 launch costs for both options, using a four-satellite constellation set-up optimised for utilisation in each case. The average satellite utilisation is the average proportion of time each satellite is providing power to a rectenna. The UK rectenna utilisation is the proportion of time the UK receives power.

Orbit option	Average satellite utilisation	UK rectenna utilisation	Launch cost per kg[13]
Circular LEO 1262 km	20.1%	21.5%	£1,100
HEO 556 km x 7,821 km	53.9%	95.7%	£1,687

The preferred orbit is calculated below. For the purposes of this calculation, global electricity delivered is valued at the highest strike price from the contracts for difference allocation round

[13] The assumptions and rationale behind launch costs in 2030 and beyond are explained in Annex A. For both LEO and HEO, it is assumed that the satellite will reach the orbit directly using SpaceX's Starship.

(AR) 6. This is a simplifying assumption; in reality, electricity prices vary according to location, market and policy incentives.

Optimal orbit calculation

The optimal orbit maximises $\mathrm{Y} = \text{ Present value(lifetime electricity)} - \text{Launch cost}$

$\text{PV(lifetime electricity)} = \text{Electricity generated per year} \times \text{Price}^{14} \times \text{Discounted lifetime}^{15} \times \text{Solar panel degradation adjustment}^{16}$

$\text{Launch cost} = \text{Mass per satellite} \times \text{Number of satellites} \times \text{Cost to reach orbit per kg}$

LEO: $\text{Electricity generated per year} = 31\text{ MW} \times 8760 \times 20.1\% \times 4 = 218{,}300\text{ MWh}$

$\mathrm{Y_{LEO}} = 218{,}300 \times £238.11 \times 5.61 \times 0.95 - 98{,}500 \times 4 \times £1{,}100 = -£156\text{m}$

HEO: $\text{Electricity generated per year} = 31\text{ MW} \times 8760 \times 53.9\% \times 4 = 585{,}000\text{ MWh}$

$\mathrm{Y_{HEO}} = 585{,}000 \times £238.11 \times 5.61 \times 0.95 - 98{,}500 \times 4 \times £1{,}687 = £78\text{m}$

Since $\mathrm{Y_{HEO}} > \mathrm{Y_{LEO}}$, it follows that HEO is the preferred orbit and it is taken forward for the rest of this study. Furthermore, technical and regulatory limitations mean that the maximum output of an MVP satellite in LEO would likely be smaller than 31MW. While launch and satellite build costs would scale proportionately, the smaller aperture of the LEO system would reduce efficiency, affirming the case for a HEO deployment.

The number of satellites and rectennas

In HEO, the minimum number of satellites required to provide near-continuous power to a UK-based rectenna is four. A smaller number of satellites would result in significantly longer periods when the UK-based rectenna receives no power.

If more than four satellites were in a constellation, then there would be a significant amount of time where multiple satellites *could* beam to the same rectenna. However, each rectenna only has the capacity to receive the power of one satellite at a time, so this duplication incurs additional cost with no benefit. It would not be desirable to construct the rectennas such that one rectenna could receive power from multiple satellites, because:

- If the rectenna were the same size, constructive interference would increase the energy intensity on the ground beyond regulatory limits.

[14] The electricity price used for the purpose of this calculation is the highest strike price from the contracts for difference allocation round 6 inflated to 2024 GBP, £238.11 (see Table 8).
[15] A lifetime of 15 years is assumed for small-scale SBSP. There is precedent for this in MEO, with the latest generation of GPS satellites forecast to have a 15-year operating life. The lifetime is discounted at a 20% hurdle rate, yielding a discounted lifetime of 5.61 years.
[16] It is assumed that solar panels degrade to 90% of their original output by end of life, so average output is 95%.

- If the rectenna were larger to capture the beam of multiple satellites, it would suffer from worse utilisation, since beam energy intensity is highest near the centre of the rectenna.

Deploying rectennas in multiple countries enables the UK to generate export revenues by providing power directly to these countries. The optimal number and position of rectennas depends mostly on geography:

- Rectennas must be sufficiently spread, longitudinally, across the globe, to avoid ‘competing’ for the power of each satellite.
- All rectennas must occupy a similar latitude so that satellites, which are optimised to provide power at that latitude, can service them all.

Given these considerations, the reference design for this study uses three rectennas, in Aberdeen (UK), Edmonton (Canada) and Sapporo (Japan).

Launch strategy

The MVP solution is sized such that the mass of a single satellite (including assembly equipment and fuel) is always less than 100 tonnes so that it can be launched with a single super-heavy launch vehicle. As technology develops through the 2030s and components become smaller and lighter, more power-producing modules are added to the design, keeping total mass constant but increasing the system’s power output capability. The launch strategy makes uses of SpaceX’s upcoming Starship.[17] It relies on Starship to:

- Have a payload capacity to LEO of at least 100 tonnes.[18]
- Be capable of in-space refuelling to reach the target HEO orbit or be capable of reaching HEO directly.
- Be available for commercial use by 2030, so that the first small-scale SBSP constellation can launch on Starship.

There is currently limited information on the payload mass Starship can directly deliver to different (particularly non-standard) orbits. If possible, Starship will launch the satellite directly into HEO. Otherwise, Starship will launch into LEO, refuel, and then carry the satellite to HEO.

Additional launch strategies were considered. In particular, a Starship delivery to LEO and then solar electric propulsion to HEO would be the cheapest solution. However, this is determined to be not technically feasible because the long transfer time would incur too much time spent in the inner Van Allen radiation belt, damaging the satellite.[19]

[17] The modelling also considers delays to Starship or use of the Falcon Heavy launch vehicle, in the case that Starship is unavailable.
[18] The payload for Starship is marketed by SpaceX as between 100 and 150 tonnes. SpaceX - Starship
[19] Analysis is conducted by Space Solar using the European Space Agency’s SPENVIS (Space Environment Information System) tool to ensure that the satellite avoids most of the radiation Van Allen belt during operation.

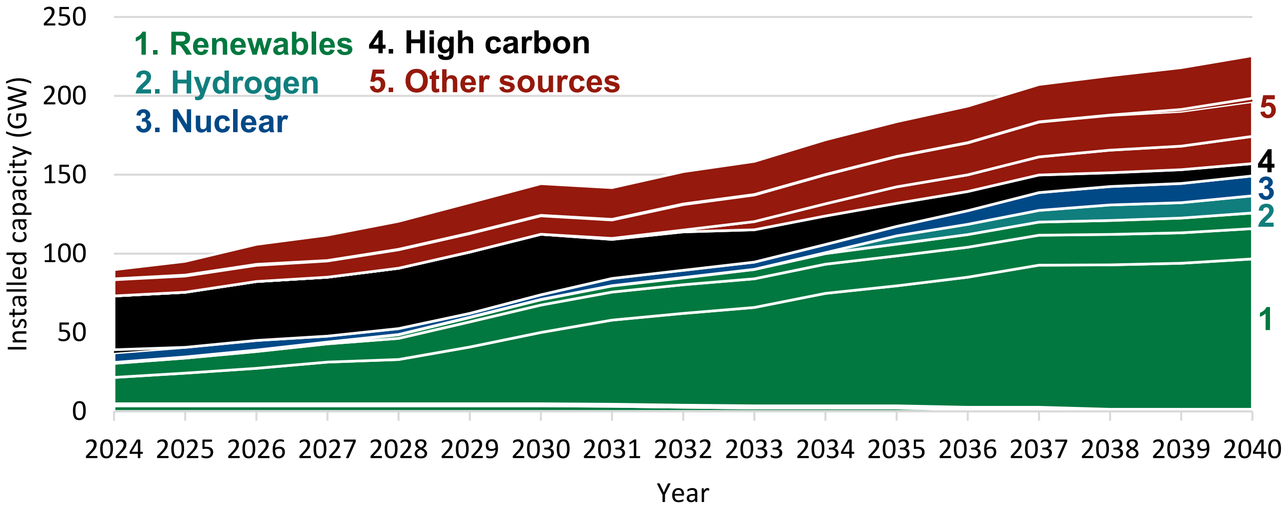
Scenarios

This study assesses how small-scale SBSP solutions may impact the GB energy market in the 2030s by defining and comparing a set of four scenarios. The first scenario provides a baseline, using existing projections of the GB energy market to understand the state without any SBSP. The next three scenarios explore how small-scale SBSP may contribute to Net Zero objectives in various forms, including a single satellite solution and two constellation solutions. The utilisation achieved under each scenario is a function of the orbit choice and rectenna location choice, which remain constant from FOAK in 2030 through to NOAK in 2040.

Scenario 1 – Baseline

The baseline scenario is aligned to NESO's Electric Engagement Future Energy Scenario (EEFES).[3] EEFES assumes the UK's effort to decarbonise the energy system is led principally by electrification. It provides detailed year-by-year projections of energy supply and demand, as well as information about future transmission and generation constraints.

Figure 1 presents the transmission capacity of the UK by generation type from 2024 to 2040 under the EEFES. Renewables include biomass, hydro, offshore and onshore wind, solar and waste. High carbon technologies include gas and coal. Other sources include interconnectors, fuel oil, marine and storage. White lines separate different types of generators that fall under the same category.



EEFES does not include SBSP as a power source in any form, and thus it provides a prediction of the state of the GB energy sector in the 2030s without SBSP. As a result, it provides a useful benchmark to contextualise the contribution small-scale SBSP could make in the other scenarios.

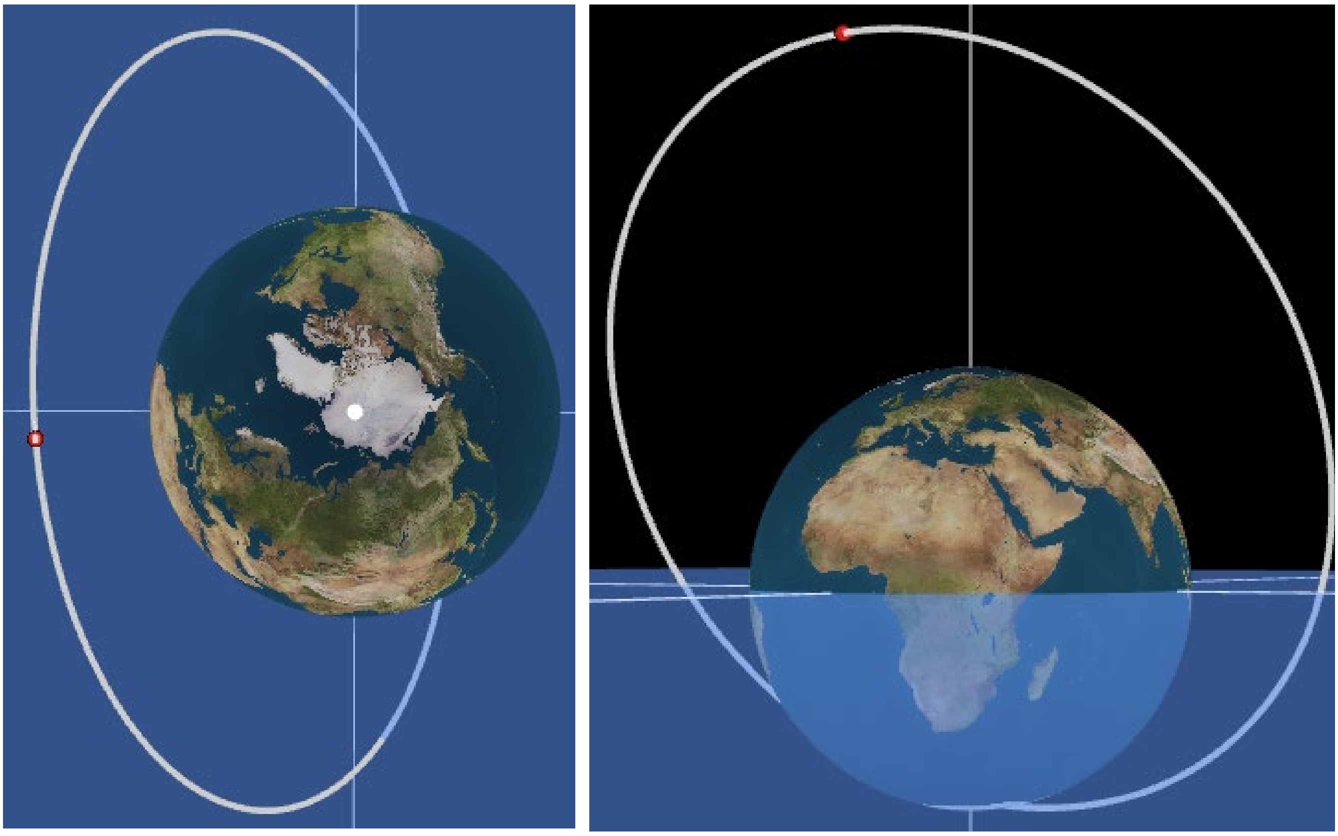
Scenario 2 – A single MVP satellite

Scenario 2 explores the case of a single satellite solution placed in a highly elliptical orbit (HEO) providing intermittent power to a single rectenna in the UK.

Table 4 details the technical specifications of the Scenario 2 orbit.

Parameter	Value
Semi-Major Axis (km)	10.56
Eccentricity	0.344
Argument of periapsis (°)	270
Ascending Node Longitude (°)	185
Inclination (°)	116.6

Figure 2 presents the Scenario 2 orbit from two angles: a bird's eye view of the X-Y plane (left) and from alongside the X-Y plane (right).[20]



Rectenna utilisation is calculated using an orbit simulation model that runs for 24 hours and observes the proportion of time each rectenna receives power. At any given point in time, a rectenna is determined to be receiving power if:

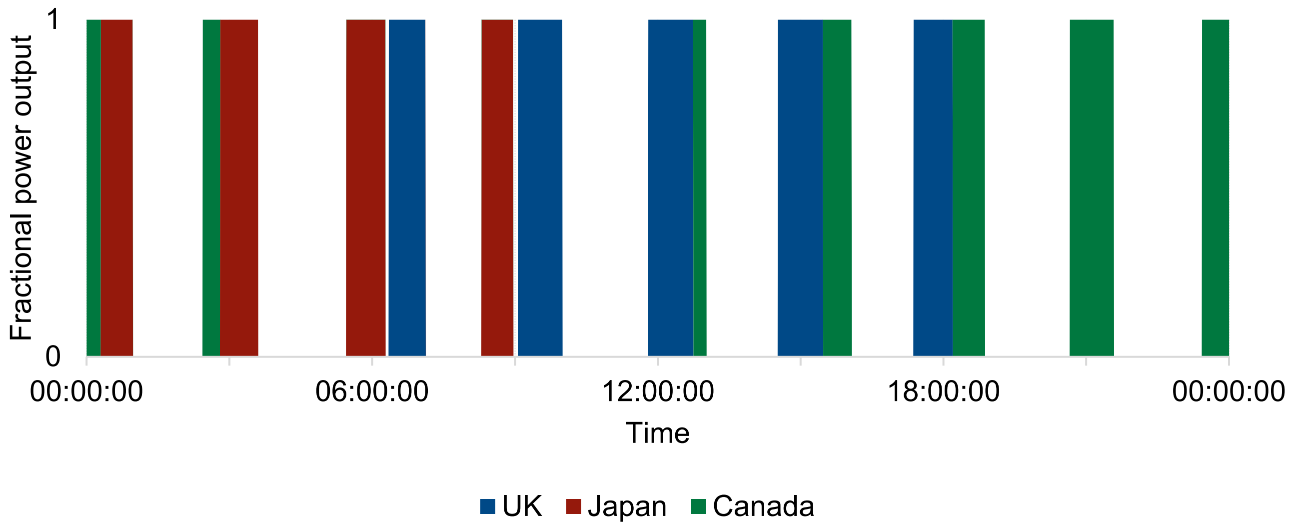
- The rectenna falls within the 'vision cone' of a satellite.[21]
- That satellite is not in eclipse and is not currently providing power to another rectenna.

[20] Images generated using [Orbital Mechanics - orbital elements visualizer and launch simulator]

[21] The vision cone of the satellite projects an ellipsis on the Earth representing the set of locations a satellite can instantaneously beam to, given its position.

The analysis prioritises the UK rectenna. If a satellite could provide power to either the UK rectenna or another rectenna, then it chooses the UK rectenna.

Figure 3 presents the Scenario 2 orbit simulation results at equinox, using UTC +00:00. The results are the same for all dates in the year.



Under Scenario 2, small-scale SBSP achieves:

- A utilisation of 18.5% in the UK, 14.9% in Japan and 15.5% in Canada.
- 48.8% overall satellite utilisation.

This implies that under Scenario 2 a single 2030 MVP satellite (capable of delivering 31 MW of power) provides 50 GWh of electricity to the UK each year and 133 GWh globally.

Scenario 3 – An MVP constellation optimised for maximum UK utilisation

Scenario 3 considers a four-satellite MVP constellation in HEO, optimised to provide maximum utilisation of the UK rectenna. Each satellite's orbit is defined by a different ascending node longitude (ANL). A satellite's ANL shifts a full 360° though a 24-hour cycle of the Earth's rotation. The Scenario 3 constellation separates each satellite by 90° so that they are evenly spread, minimising the wasteful overlap that occurs when two satellites are in range of the same rectenna and cannot provide power to another location.

Table 5 details the technical specifications of the Scenario 3 orbit.

Parameter	Value(s)
Semi-Major Axis (km)	10.56
Eccentricity	0.344
Argument of periapsis (°)	270

Ascending Node Longitude (°)	28, 118, 208, 298
Inclination (°)	116.6

Figure 4 presents the Scenario 3 orbit from two angles: a bird's eye view of the X-Y plane (left) and from alongside the X-Y plane (right).

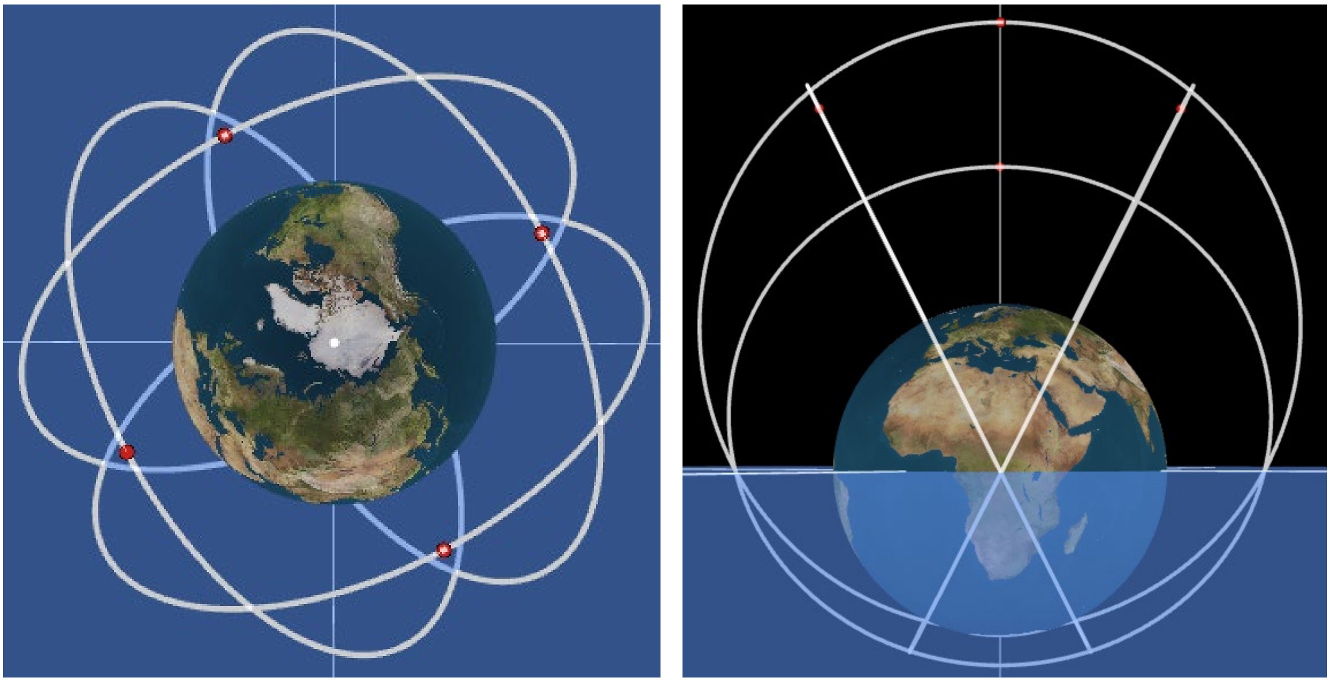
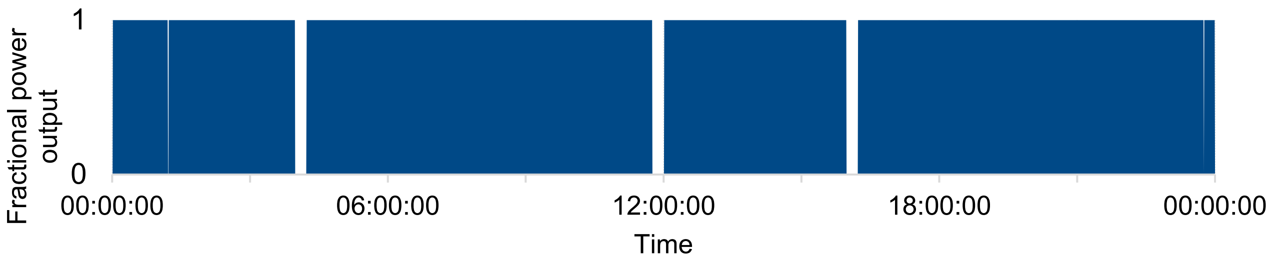
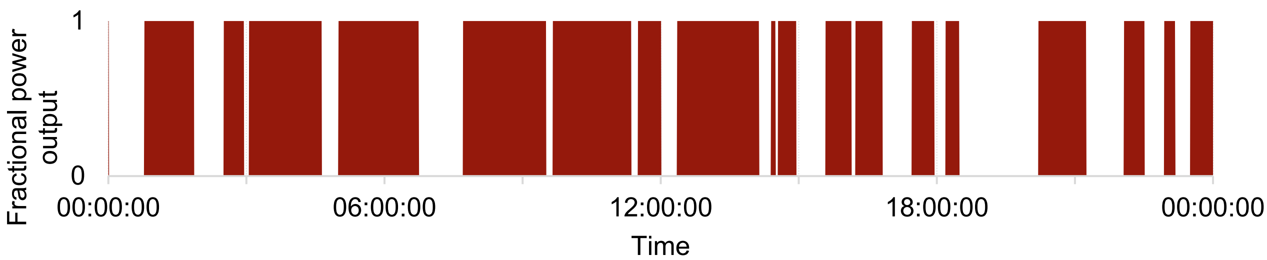


Figure 5 presents the Scenario 3 orbit simulation results using UTC +00:00.

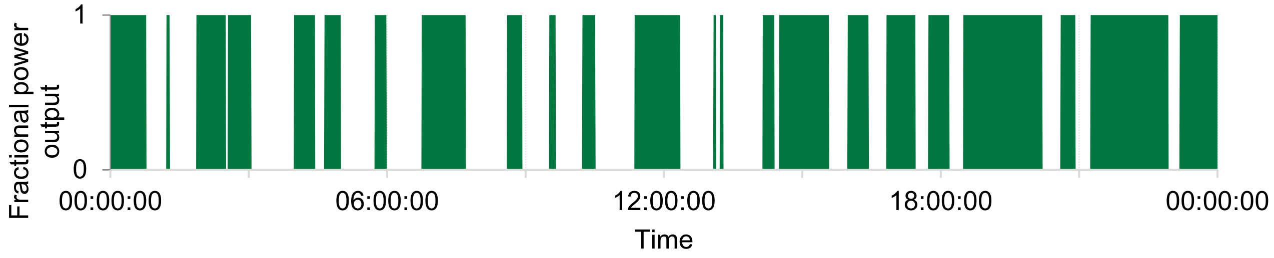
UK



Japan



Canada



Under Scenario 3, power is provided at:

- A utilisation of 95.7% in the UK, 64.0% in Japan and 55.7% in Canada
- 53.9% average satellite utilisation.

This implies the Scenario 3 constellation can provide 260 GWh of electricity to the UK and 585 GWh globally each year under the 2030 FOAK satellite specification.[22]

Scenario 4 – An MVP constellation optimised to provide maximum power at dawn and dusk

Scenario 4 is an alternative four-satellite constellation in HEO. It considers a configuration of four satellites with the profile set out in Scenario 2 designed to maximise the power provided to the UK at periods of peak power price i.e. dawn and dusk. By providing power at this time, small-scale SBSP is likely to be more valuable because it:

- Provides power when energy prices are typically highest.
- Provides a predictable source of low carbon generation at a time when other renewables, (notably terrestrial solar) cannot generate, thereby potentially displacing dispatchable fossil fuel generators that would otherwise be used, reducing energy system costs and emissions.
- Reduces balancing costs, which are exacerbated at times of peak energy demand.

Scenario 4 is defined as the combination of Scenario 2 satellites that maximises the average Intermittent Market Reference Price (IMRP) of delivered power over a typical 24-hour period.[23] The maximisation exercise shows that the optimal constellation arrangement has two ‘trains’ of two satellites, with the trains offset from each other to provide power to the UK at the best time. Compared to Scenario 2, the energy profile is the same, except:

- The first train provides power 30-minutes later than in Scenario 2.
- The second train provides power 1 hour and 30-minutes later than in Scenario 2.

[22] Note that the constellation could also be optimised to provide high-utilisation power in other countries (such as Japan or Canada), rather than the UK.
[23] This analysis used the average IMRP at each time of day (in 30-minute increments) Between the period 2023 to 2024

This is equivalent to an increase in ANL of 7.5° and 22.5°, respectively, compared to the Scenario 2 orbit.

Table 6 details the technical specifications of the Scenario 4 orbit.

Parameter	Value
Semi-Major Axis (km)	10.56
Eccentricity	0.344
Argument of periapsis (°)	270
Ascending Node Longitude (°)	192.5, 207.5
Inclination (°)	116.6

Figure 6 presents the Scenario 4 orbit from two angles: a bird's eye view of the X-Y plane (left) and from alongside the X-Y plane (right).

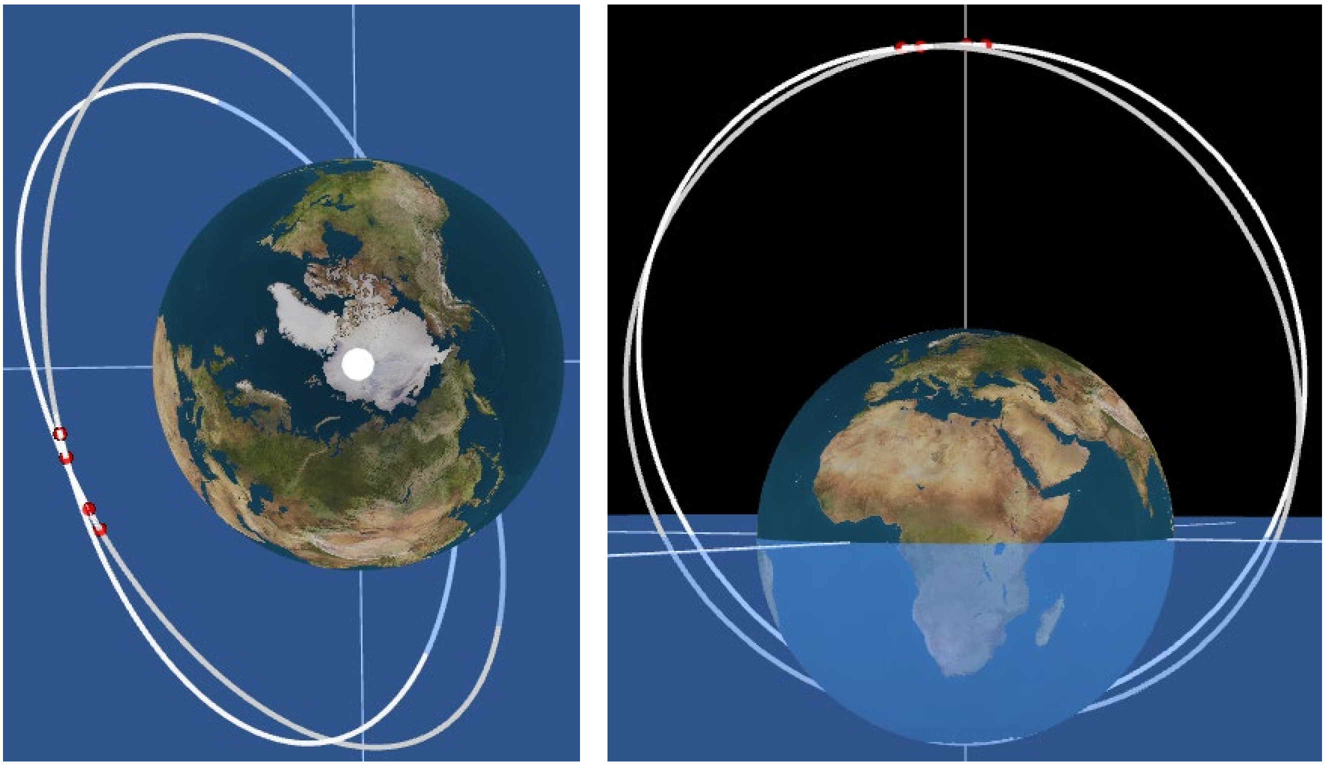
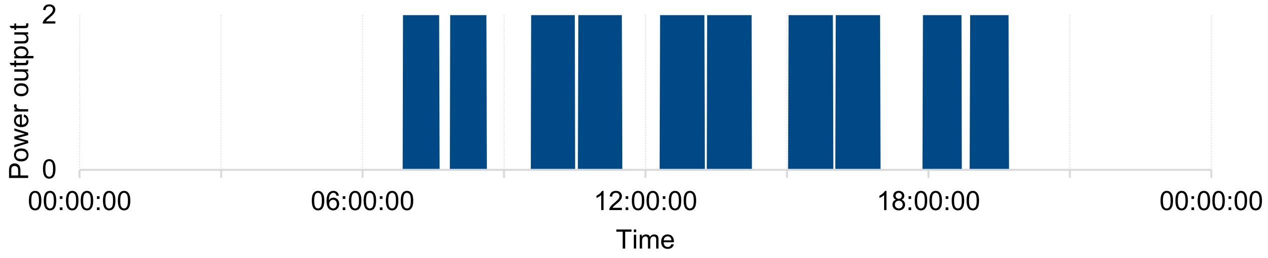
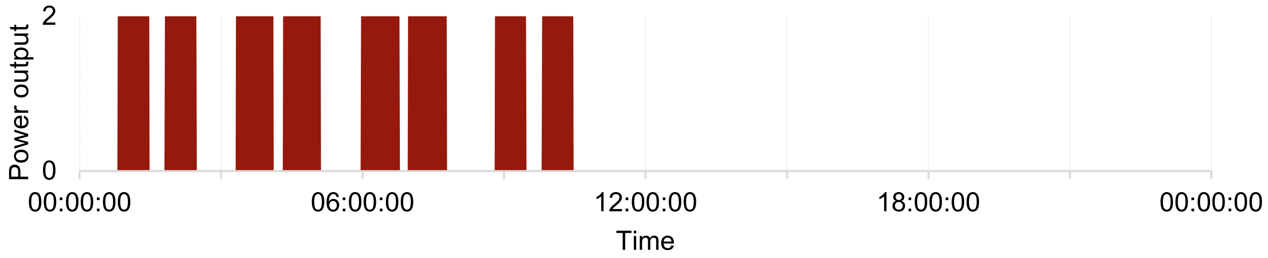


Figure 7 presents the Scenario 4 orbit simulation results at equinox for the UK, Japan and Canada respectively. Note that the y-axes are either zero or two: this reflects that, under Scenario 4, exactly two satellites provide power to a given location at a time.

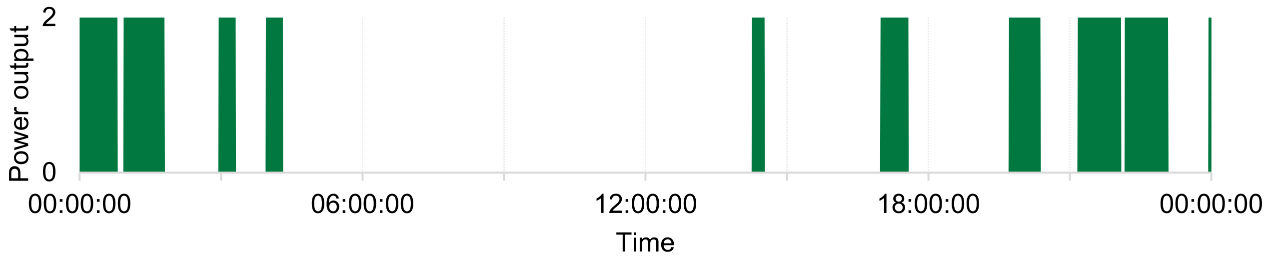
UK



Japan



Canada



Under Scenario 4, power is provided by two satellites at a time. Two rectennas are required in each location to receive this power.[24] Under this arrangement, a 2030 MVP solution provides:

- 62 MW of power at a utilisation of 39.0% in the UK, 29.8% in Japan and 31.0% in Canada.
- 48.8% average satellite utilisation.

This leads to provision of 212 GWh of energy to the UK each year and 530 GWh globally, for the FOAK 2030 system.

[24] The one-to-one relationship between satellites and rectennas is explained on pages 17-18.

4. Small-scale SBSP as a low-carbon technology

This section investigates the relative costs and benefits of small-scale SBSP when compared to an array of other low-carbon technologies, including detail on the role of small-scale SBSP in de-risking and technologically advancing larger systems.

Small-scale SBSP offers a unique set of properties compared to mainstream low-carbon generation technologies. It can provide predictable, dispatchable power, providing energy when it is most needed. Through different constellation set-ups (determined before launch), it can provide power almost 24-hours a day, or it can provide intense bursts of power optimised for when energy demand is highest.

The properties of small-scale SBSP provide several benefits:

- **Reliable all weather predictable generation.** Small-scale SBSP has a high load factor and is reliable in all weather (with a small efficiency loss of ~2% in heavy precipitation). Compared to other low-carbon technologies, small-scale SBSP has significantly more potential to engage in capacity markets by providing predictable, flexible power at peak times.
- **The ability to generate export revenues.** By placing rectennas in suitable locations across the world, the UK can export predictable, intermittent power without the need for physical transmission infrastructure. Under the orbits selected in this study, the UK exports to Canada and Japan; small-scale SBSP is sufficiently flexible to accommodate different export partners on alternative orbits, as desired.
- **Location flexibility, which can be used to minimise grid balancing costs.** At the planning stage, the location of the rectenna in the UK is flexible. While this study considers a rectenna in Aberdeen, placing the rectenna in a different UK location would not have a significant impact on when power can be received. It is possible to site a rectenna in the south of England near the areas of highest demand, which would reduce grid balancing and transmission costs.[25]
- **Technological spillovers.** There are likely to be substantial spillover effects from SBSP research and development efforts to areas including assembly of large structures in space, wireless power transmission, semiconductors and photovoltaic technology.
- **Contribution to de-risking large-scale SBSP systems.** The modularity of SBSP systems means that the technological development of a small-scale system directly contributes to de-risking large-scale systems. The introduction of small-scale SBSP is likely to reduce the hurdle rate, increase the performance, and reduce the cost of large-scale SBSP systems, contributing to a lower LCOE for these systems in the long term.[26]

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[25] The impact of rectenna location is explored in detail on pages 39 to 45.
[26] The contribution of small-scale SBSP to large-scale systems is explored on pages 29 to 30.

Table 7 summarises an analysis of the characteristics eight low-carbon technologies.

Low-carbon technology	Dispatchability	Intermittency	Predictability	Location flexibility	Technical risk	Social & environmental impact
Small-scale SBSP	High	Low	High	High	High	Medium
Large-scale solar	Low	High	Low	Medium	Low	Medium
Solar with short duration storage	Medium	Medium	Medium	Medium	Low	Medium
Offshore wind	Low	High	Low	Medium	Low	Low
Onshore wind	Low	High	Low	Medium	Low	Medium
Large-scale hydro storage	High	Low	High	Low	Low	Medium
Tidal stream	Medium	Medium	High	Low	Medium	Medium
Nuclear	Medium	Low	High	Medium	Low	Medium

Table 8 compares low-carbon technologies quantitatively, using baseline LCOE estimates in 2024 GBP.[27] Small-scale SBSP is considered FOAK in 2030 and NOAK in 2040. The maturities of other technologies at these dates are different.

Low-carbon technology (LCT)	Reference plant size (MW)	Average Load Factor	NOAK hurdle rate	Estimated LCOE (2030)	Estimated LCOE (2035)	Estimated LCOE (2040)
Small-scale SBSP	31 - 52	95.7%	9.06%	335 - 595	154 - 249	87 - 129
Tidal stream	20 - 30	38.0%	9.4%	242	150	118
Large-scale nuclear [28]	3300	90.0%	8.9%	91 - 130	91 - 130	91 - 130
Large-scale solar	20	11.1%	5.0%	44	38	36
Solar with storage	20	15.4%	-	50	44	42
Offshore wind	1000	40.5%	6.3%	46	51	49
Onshore wind	51	26.0%	5.2%	43	43	43
Large-scale hydro storage	11	45.0%	5.4%	92	92	92

By 2040, it is anticipated that small-scale SBSP's LCOE will be competitive with nuclear and tidal stream technologies. A key driver of this progress is the hurdle rate, which is anticipated to fall from 20% to 9.1% from FOAK in 2030 to NOAK in 2040. Hurdle rate alone is responsible for a 42% fall in LCOE from FOAK to NOAK. Further discussion on LCOE (and its limitations) is provided in Chapter 6.

[27] Sources include Digest of UK Energy Statistics (DUKES); DESNZ electricity generation costs; Utility-scale solar, Seel et al. (2024); The symbiotic relationship of solar power and energy storage in providing capacity value, Sodano et al. (2021); Electricity storage costs and renewables, costs and markets to 2030, IRENA (2017). Where load factors are available from DUKES, the average load factor from 2018 to 2023 is used. Otherwise, the 2025 load factor from DESNZ's electricity generation costs 2023 publication is used.

[28] Updated values for nuclear power are not available. Values are taken from BEIS_Electricity_Generation_Cost_Report.pdf using the NOAK LCOE, inflated to 2024 GBP. It is assumed that the LCOE does not change from 2030 to 2040.

The role of small-scale SBSP in developing the viability of large-scale SBSP

Roadmap

The small-scale SBSP MVP examined in this study is part of the broader development roadmap of the CASSIOPeiA reference design. This roadmap is designed to test, develop and mature the key subsystems associated with CASSIOPeiA, enabling design iteration and providing tangible milestones to de-risk later stages. The anticipated timescales for this roadmap are as follows:[29]

- In **2024**, the first 360° wireless power transmission system was successfully demonstrated. The system allows for power transmission in all directions without any moving parts, integral to the reference design's ability to transmit power precisely as it orbits Earth.[30]
- In **2026**, a further demonstration is anticipated. This will test terrestrial long-distance wireless power transfer from the ground. It will also use a prototype module with integrated photovoltaics; testing the technology that enables SBSP to generate power.
- In **2027-28**, a final demonstration is planned to demonstrate SBSP in orbit. It will test power beaming from space and structural truss assembly and should be capable of providing kilowatt-scale power.
- In **2030**, the MVP is forecast to launch, providing 31 MW of power from HEO.
- In **2033**, a larger system is planned to launch, providing 150 MW of power from the same HEO orbit. This system should be able to reach the 230 W/m^2 power intensity limit, reducing the cost of capturing a given quantum of energy.[31]
- In **2036**, the first GEO system is forecast to launch, providing 650 MW of power. Its position in GEO should enable this system to provide near-continuous power to a UK-based rectenna.

Ongoing development work between Space Solar, DESNZ and UKSA continues to mature the CASSIOPeiA design, which—as of this study—has reached concept maturity level (CML) 4 for the space segment, CML 3 for the ground segment, and CML 2 for the robotic assembly system.[32]

The contribution of small-scale SBSP

Under the reference CASSIOPeiA design, small-scale SBSP is expected to contribute to the development of a larger-scale system by:

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[29] Estimated timescales only. Actual timescales are subject to availability of funding, regulatory requirements and technological developments

[30] Space Solar - Space Solar Demonstrates World's First 360° Wireless Power Transmission

[31] An intensity limit of 230 W/m^2 is assumed in line with Frazer-Nash's SBSP Engineering Feasibility Report

[32] Concept Maturity Levels Defined

- Providing a lower first system cost that is more palatable for investors, enabling SBSP to be launched earlier. This provides an opportunity to prove the technical and commercial viability of the technology and is likely to reduce the hurdle rate of a FOAK large-scale system.
- Accelerating technical progress through learning-by-doing, improving the performance and reducing the cost of a FOAK large-scale system.

These benefits would reduce the LCOE of a large-scale system, enabling faster progress towards a GW-scale SBSP system that could provide large-scale, economically attractive power to the GB grid. Two key assumptions govern this assertion:

1. There must be a strong sustained demand signal for SBSP, including for small and large-scale systems.
2. The small-scale system must successfully demonstrate the key capabilities of SBSP and make the anticipated technical progress throughout the 2030s.

Without small-scale SBSP, it is assumed that the first large-scale SBSP FOAK system will require a hurdle rate of 20%.[4] It is possible that the de-risking effect of the small-scale system will unlock a more competitive capital structure, equivalent to the hurdle rate of the small-scale system in 2035 (13.1%).[33]

Table 9 presents the potential impacts of small-scale SBSP on the LCOE of a large-scale system through hurdle rate.

Scenario	Assumed hurdle rate	Reduction in large-scale SBSP LCOE
No effect	20%	0%
Part de-risking	16.6%	16%
Full de-risking	13.1%	27%

Additionally, small-scale SBSP is expected to contribute to technical improvements by leveraging learning-by-doing to develop new, more advanced technology throughout the 2030s. Space Solar anticipate technological advancements will be rolled out every few years through new module 'generations'.[34] By 2036, Space Solar anticipate third-generation modules will be available. If sufficient technological progress is achieved, these modules will be cheaper and lighter than the generations before, further decreasing the LCOE of a large-scale SBSP system.[35]

[33] This assumption is based on capital structure modelling by Space Solar
[34] Please see Annex A for more.
[35] The impact on large-system LCOE is not quantifiable as part of this study. Unlike hurdle rate, it cannot be related to the 2021 Frazer-Nash study because the large-scale system's technical parameters have changed.

5. The market opportunities for small-scale SBSP

This section identifies the market opportunities for small-scale SBSP, exploring contracts for difference, GB ancillary markets and ten global markets.

GB energy market opportunities

Contracts for Difference (CfD)

The CfD scheme is the Government's main policy for supporting new low carbon generators.[36] Generators operating under the scheme have a contract with the Low Carbon Contracts Company (owned by DESNZ) that guarantees to pay them a set price—*the strike price*—for each MWh of energy supplied to the market. This transfers the risk of variable power prices from the generator to the Government and consumers and allows the generator to secure a lower cost of capital from lenders, leading to significant reductions in overall project costs.

CfD are awarded through an annual auction process (*Allocation Rounds* – AR), with the Government setting various parameters, such as the maximum strike price (*Administrative Strike Price* – ASP), the size of the budget available for support and a target total energy generation capacity. Contracts have a typical length of 15 years, during which time winning generators will receive their (index linked) strike price for the energy sold. The ASP varies according to technology type, allowing flexibility in the levels of support that are provided. **ASP are defined in 2012 GBP**. Table 8 provides AR6 auction results for a range of technologies.

Table 10: The latest AR6 CfD auction results, with the strike price inflated to 2024 GBP[37]

Technology	Total Capacity	Strike Price		ASP
	MW	£/MWh 2012	£/MWh 2024	£/MWh 2012
Solar PV (>5MW)	3,288.31	50.07	69.32	61
Onshore Wind (>5MW)	990.37	50.9	70.46	64
Tidal Stream	28	172	238.11	261
Floating Offshore Wind	400	139.93	193.72	176
Offshore Wind	3363.07	58.87	81.5	73

[36] CBP-9871.pdf – Contracts for Difference, House of Commons Library, 14 October 2024
[37] Contracts for Difference Allocation Round 6 results

The generator participates in the energy markets in the normal way, contracting to generate and then receiving the market price revenues from the energy that it sells. The CfD mechanism applies retrospectively and uses sets of reference market prices to assess whether a CfD participant should receive top-up payments to reach its strike price, or if it needs to payback surplus earnings in excess of the strike price. There are two sets of reference prices:

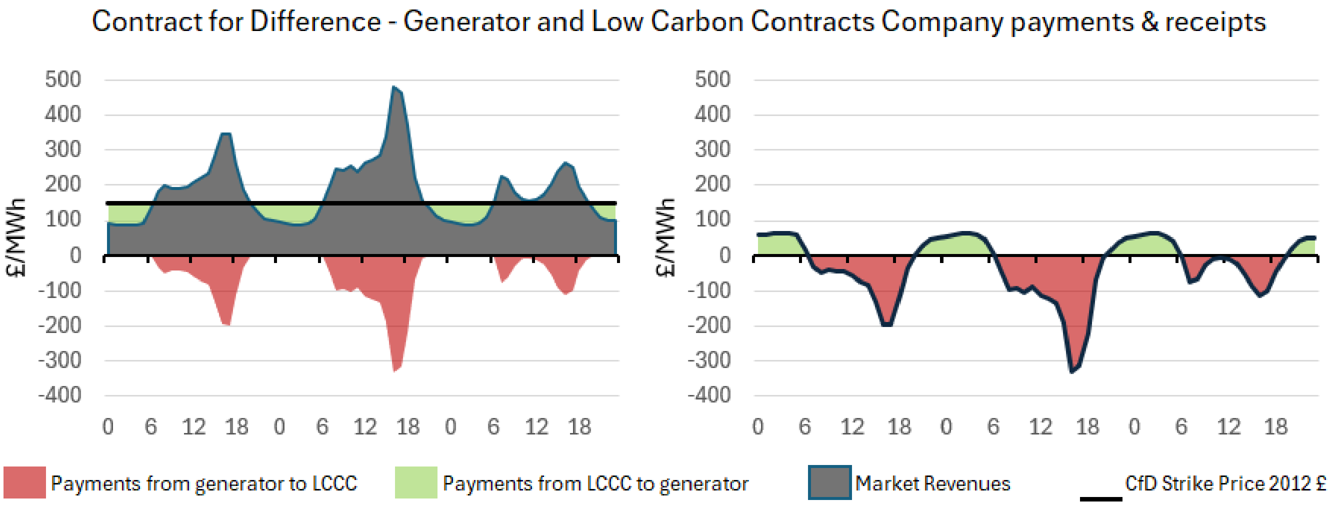
- The Intermittent Market Reference Price (IMRP) is a set of half-hourly energy prices calculated using day-ahead price data[38]. It is used as the reference price for intermittent generators.
- The Baseload Market Reference Price (BMRP) is calculated on a seasonal basis and is the reference price applied to generators that can supply (near) continuous power, for example biomass and Combined Heat and Power (CHP) options[39]. This is established for six-month periods.

Either baseload or intermittent could be applicable to small-scale SBSP, depending on the constellation configuration that is chosen.

SBSP as an intermittent generator

The process is illustrated for an intermittent generator in Figure 8: in any settlement period in which the generator sells energy, its net revenue per MWh will be accrued at the strike price.

Figure 8: Illustration of the CfD mechanism for an intermittent generator. The lefthand plot shows the makeup of the generator's final revenue per MWh sold: a combination of market revenues and receipts from and payments to the Low Carbon Contracts Company. The righthand plot separates out the LCCC contribution. Values are for illustration only.



If small-scale SBSP is provided on an intermittent basis (i.e. Scenario 4) it can expect to receive payment via the market at (approximately) the IMRP reference price at those times of day when it is able to provide GB power. Where this IMRP price lies below the strike price, the

[38] How Intermittent Market Reference Price (IMRP) will be calculated from 1 January 2021 - Low Carbon Contracts
[39] https://www.emrsettlement.co.uk/document/guidance/g24-cfd-generator-payments/ - G24 CfD Generator Payments, 29 January 2025

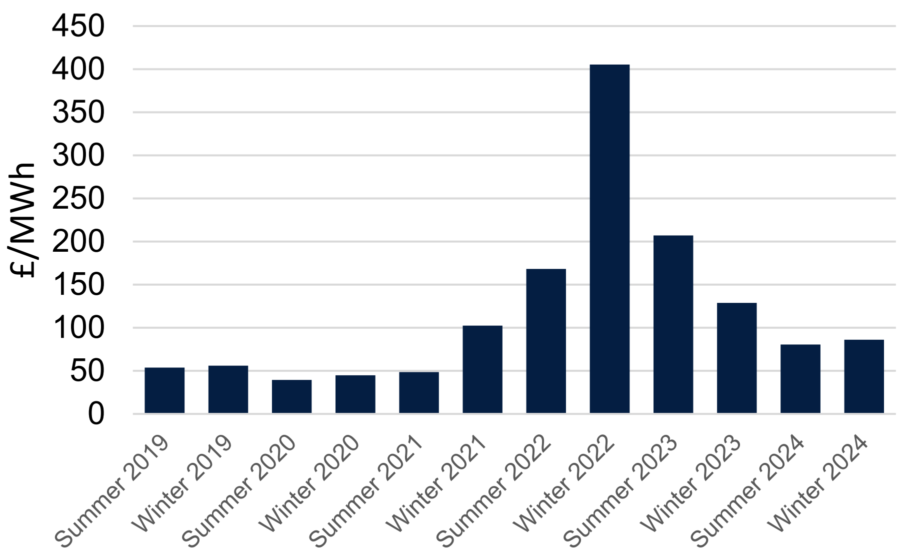
LCCC will provide a top-up. Should the IMRP exceed the strike price, the difference is repaid to the LCCC.

The average variability in IMRP price throughout the day typically follows a bi-modal pattern which broadly follows the daily cycle of electricity demand. There is a large peak in the late afternoon/early evening, and a lesser peak around dawn. Prices are at a minimum at night when demand is at its lowest. CfD top-up payments will therefore be minimised if the satellite orbit can be configured so as to maximise delivery at time of peak prices, and minimise power supplied at night. There is currently no mechanism within the CfD process to incentivise generators to prioritise power delivery in this way.

Small-scale SBSP as a baseload generator

If small-scale SBSP is provided as baseload, it would be subject to the BMRP prices, with historical values shown in Figure 9. These prices are fixed twice-yearly: a summer price and a winter price, with the same approach to payment and receipt of differences to the LCCC.

Figure 9: Baseload Market Reference Prices (£/MWh) from 2019 to present.[40]



Ancillary market opportunities

Ancillary services support the reliable, stable and efficient transmission of electrical energy around the grid. This includes maintaining the supply voltage, keeping the frequency within agreed margins (Dynamic services), ensuring that the system is robust to faults and can restart in the event of blackout, and that it has adequate reserve in hand to deal with unexpected occurrences. Traditionally, fossil-fuelled generators were the main source of ancillary services. These are being lost in the transition to renewable and, to counter this, markets are currently being established to incentivise new providers to replace them, while simultaneously driving down both carbon emissions and costs for consumers. This is a rapidly changing space that may present opportunities for small-scale SBSP to earn some further revenues alongside sales of active power into GB energy markets. However, it is worth noting that the total size of the

[40] Settlement Data for CfD Generators - EMR Settlement Limited

ancillary markets is small compared to sales of active energy and could only provide limited uplift to revenues.

In Annex B we provide a full snapshot of the current range of GB ancillary services with a brief assessment of whether small-scale SBSP might be able to contribute. Opportunities for significant additional revenue seem limited, particularly without the inclusion of a battery within the small-scale SBSP system. This is summarised below:

- Participation in most markets would require (presumably) each GB-based rectenna to be registered as a Balancing Mechanism Unit (BMU).
- The ability to provide or absorb reactive power is a requirement of obtaining a grid connection. This is known as the Obligatory Reactive Power Service (ORPS). How often this is required, and the quantities involved are strongly locationally dependent. A payment is received should a generator be asked to provide reactive power. The payment rate received is calculated monthly with prices of between £3.90 and £5.20/MVarh,[41] observed over the course of 2024[42].
- Frequency response services are contracted over 4-hour windows (electricity forward agreement (EFA) blocks), during which the supplier must be available to respond (on timescales of seconds or less) if required. For this reason, delivery of these services would only be possible if the rectenna were co-located with a battery that could ensure delivery at any time within the EFA block.
- Reserve services could potentially be offered. These fall into positive reserve (ability to turn up output if required) and negative reserve (ability to turn down if required). Unless the SBSP unit were to withhold some of its capacity (thereby foregoing CfD and active power payments), it would be unable to offer positive reserve. Negative reserve would entail scaling back output. The CfD would still be received as per the original contracted power amounts, but additional revenue would be available if turn down were requested. At the moment, prices in the Negative Balancing Reserve market are capped at £1.55/MW for each settlement period (30-minutes).

Global market opportunities

Beyond GB grid-connected opportunities, there are several other worldwide market opportunities for small-scale SBSP. These opportunities are identified as being serviceable by a small-scale system within the 2030s. A single small-scale system does not necessarily provide all the power required in each case; rather, it is anticipated that it will supplement the existing energy mix of these applications.

[41] Megavolt-Amperes Reactive Hour (MVArh) is a unit of measure for reactive energy.
[42] reactive-default-payment-rate-mar-2025.pdf

Table 11 identifies ten global markets, summarising the need for SBSP and calculating market sizes, including estimates for total addressable market (TAM), serviceable addressable market (SAM) and serviceable obtainable market (SOM). Annex C provides the market analysis in full, including justification for market sizes and further narrative.

Market	Annual TAM (TWh)	Annual SAM (TWh)	Annual SOM (TWh)
Small island nations	220,500	1,544	772
Iron and steel production	3,056	511	306
Mining	5,000	600	300
Green hydrogen production	902	433	216
Dual use with terrestrial solar	1,005	201	100
Data centres	945	57	28
Water desalination	120.5	36	18
Cold ironing for merchant shipping	24	6.7	3.4
Deployed operating bases	2.64	0.4	0.2
Polar research stations[43]	0.56	0.13	0.06

[43] Polar research stations would be serviced by a constellation in polar LEO. Detail is provided in Annex C.

6. An economic assessment of small-scale SBSP

This section analyses whether small-scale SBSP is supportable under current CfD precedents while remaining commercially viable, accounting for LCOE, energy system benefits and any further sources of supplementary funding.

LCOE

This study uses LCOE to measure small-scale SBSP's economic viability in relation to alternative sources of generation. Up-to-date LCOE values are readily available for a range of generation technologies, making it a useful tool to compare relative lifetime costs of energy.

Limitations of LCOE

LCOE is an imperfect measure of economic viability because it does not capture all relevant costs. In particular, LCOE does not account for the system costs of intermittency and the non-dispatchable nature of variable renewable energy sources such as wind and solar. Alternative estimation methodologies, such as levelised full system cost of energy (LFSCOE), begin to account for these costs. Emblemsvåg (2025) estimates that the LFSCOEs of wind and solar in Germany are an order of magnitude higher than their LCOEs—demonstrating the scale of system costs that LCOE alone does not capture.[44] However, further work is needed to define and standardise LFSCOE in order to enable a fair comparison between technologies—LFSCOE estimates are highly sensitive to assumptions about energy system configuration and future flexibility, which vary widely between countries.

In the UK, the effect may be smaller: UK government analysis places offshore wind's 'enhanced LCOE' between 1.4 and 2.1 times its LCOE.[45] Importantly, the energy supplied by small-scale SBSP is predictable, flexible and, dependent on configuration, not intermittent, so its LFSCOE (or enhanced LCOE) is likely to be much closer to its LCOE. Therefore, small-scale SBSP is likely to be more economically competitive with variable renewables than its LCOE alone would suggest.

The LCOE of small-scale SBSP is highly influenced by a small number of factors, including power output, hurdle rate, launch costs, rectenna build costs and satellite build costs. The values of these inputs are expected to change from the FOAK implementation in 2030 to NOAK in 2040.

[44] Rethinking the "Levelized Cost of Energy": A critical review and evaluation of the concept - ScienceDirect
[45] Electricity Generation Costs 2020

Table 12 lists a subset of model inputs under the central baseline scenario, from FOAK in 2030 to NOAK in 2040. A full account of model inputs and justification for these values is provided in Annex A.

Input	Value in 2030	Value in 2035	Value in 2040
Power output (MW)	**31**	**42**	**52**
Hurdle rate (%)	**20.0**	**13.2**	**9.06**
Launch cost (£/kg to HEO)	1650	1400	1150
Rectenna cost (£ million per km^2)	7.99	7.20	6.43
Satellite build cost (£ million, each)	103	61.1	38.8

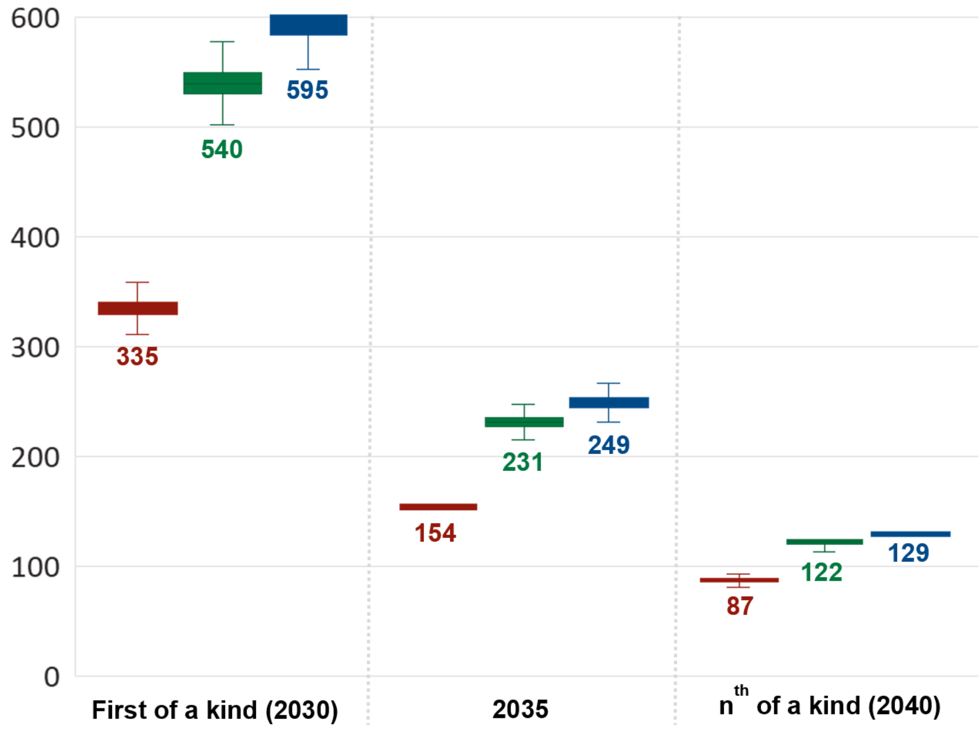
The baseline estimate is constructed using mildly conservative assumptions such as 20% hurdle rate. More optimistic launch cost, build costs and hurdle rate assumptions could be made. Two variations on the baseline are constructed to test the impact of adjusting several input values at once:

- **The optimistic baseline** removes optimism bias adjustments, uses moderately ambitious launch costs and uses a lower hurdle rate of 14.9% at FOAK instead of 20%, scaling at the same rate as the baseline case thereafter. The lower hurdle rate reflects the less risky nature of a smaller-scale system, compared to the large-scale system analysed in Frazer-Nash's 2021 report.[4]
- **The conservative baseline** adds further optimism bias adjustments to satellite and assembly equipment build costs. The adjustment applied is 100% instead of 50%.

Table 13 presents the median cost estimates for each baseline from FOAK to NOAK.

Baseline variation	2030 LCOE (£/MWh)	2035 LCOE (£/MWh)	2040 LCOE (£/MWh)
Optimistic	335	154	87
Central	540	231	122
Conservative	595	249	129

Figure 10 visualises the LCOE estimates. For each date, leftmost estimate = optimistic baseline (red); middle = central baseline (green); rightmost estimate = conservative (blue).



The uncertainty in LCOE estimates is driven by the variability of model inputs.

Table 14 summarises the four most influential inputs on average.

Input	Variance contribution – 2030 (%)	Variance contribution – 2035 (%)	Variance contribution – 2040 (%)
Launch cost	55.5	62.9	64.0
Rectenna cost	13.6	17.3	20.8
Satellite build cost	22.3	12.4	7.5
Other capex	5.6	4.8	5.2

Launch costs contribute increasingly to uncertainty throughout the 2030s, reflecting the increasing proportion of overall costs that can be attributed to launch. By contrast, satellite build costs are expected to decline more quickly, reducing their share of total system cost and thus their influence on LCOE.

Sensitivity analysis

Sensitivity analysis is conducted by varying **individual** inputs one at a time, relative to the central baseline. The LCOE analysis is repeated for several input variations, exploring the impact of:

- External factors, such as launch costs and hurdle rate.

- Internal cost factors, including satellite and rectenna build costs.
- Internal technical factors, including power output and operational lifetime.

The full sensitivity analysis and input variation definitions are provided in Annex A.

Table 15 summarises the median LCOE estimates under some of the considered scenarios.

Input variation	2030 LCOE (£/MWh)	2035 LCOE (£/MWh)	2040 LCOE (£/MWh)
Starship delayed	600	250	145
Module upgrades delayed	540	277	169
Slower hurdle rate progression	540	272	162
14.9% FOAK hurdle rate	434	194	106
Best case launch costs [46]	362	149	84

Energy system benefits

Whole energy system modelling is conducted to understand how small-scale SBSP provides monetisable benefits that are not captured within LCOE estimates. The model is configured to represent the GB energy system in 2035 under the electric engagement future energy scenario (EEFES). The model uses the UK rectenna energy profiles to calculate the capacity of alternative generators that is displaced by small-scale SBSP and to quantify energy system benefits.

The model considers three types of costs and benefits:

- **Revenue (R)**, including the recovered cost of electricity being exported to Europe via interconnectors.
- **Opex (O)**, including hydrogen and carbon capture and storage (CCS) operating costs and the operating costs of electricity generation (mostly gas, biomass and nuclear).
- **Capacity-related costs (C)**, including the costs of transmission, distribution and interconnection; energy generation capital costs, and the capacity-related costs of hydrogen and CCS.

The model determines how whole energy system revenue, Opex and capacity costs change as small-scale SBSP is introduced to the system. It is likely to underestimate the true benefits of small-scale SBSP because:

[46] This cost is much more ambitious than any of the baseline variations, assuming $200/kg to LEO by 2040.

- It includes only energy that is transmitted to the UK. The UK's export partners (Canada and Japan, in this study) are also likely to receive energy system benefits which are not quantified.
- Iteration would be required to identify the constellation arrangement that provides the UK rectenna utilisation profile maximising energy system benefits.
- The impact of small-scale SBSP is calculated by scaling down a notional system with 1 GW output. If the marginal benefit of SBSP were a decreasing function of capacity, then this would mean the small-scale system's benefit is underestimated.[47]

The energy system model compares two scenarios to the counterfactual (Scenario 1):

1. Scenario 3 (maximum utilisation) with a rectenna sited in Aberdeen or in the south of England, near London.

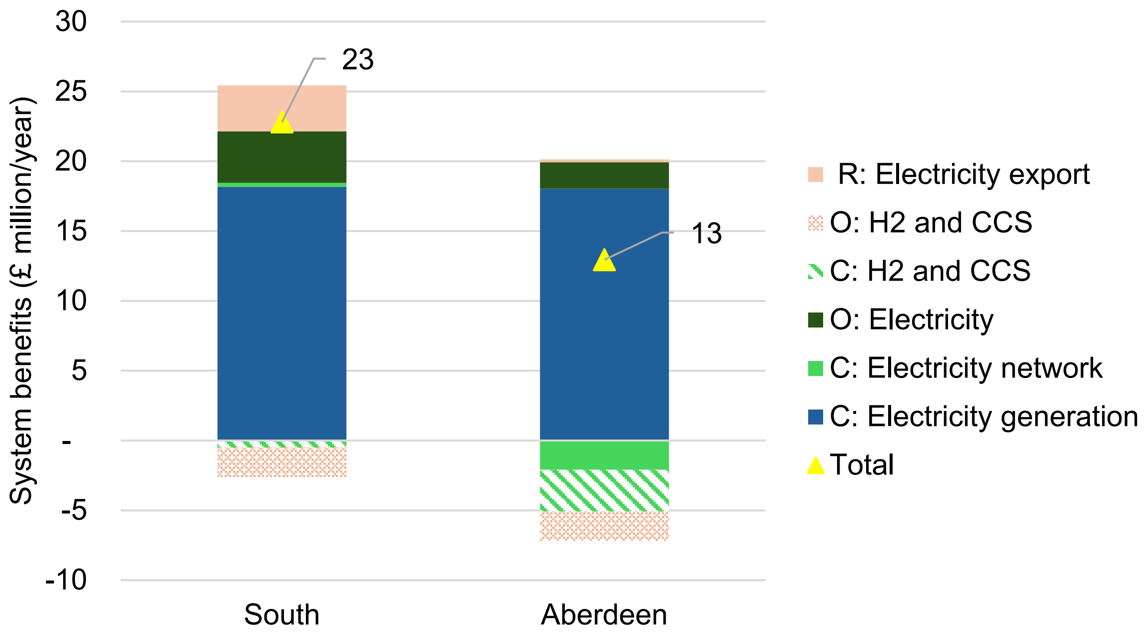
2. Scenario 4 (dawn/dusk) with two rectennas sited in Aberdeen or in the south of England, near London.

Scenario 3 – Maximum utilisation

Under Scenario 3, 52 MW of SBSP—provided by a NOAK system in 2040—is expected to generate energy system benefits of:

- £12.9 million per year if the rectenna is sited in Aberdeen.
- £22.8 million per year if the rectenna is sited in the south of England.

Figure 11 presents the energy system benefits associated with 52 MW of small-scale SBSP under Scenario 3 in the south of England and in Aberdeen.



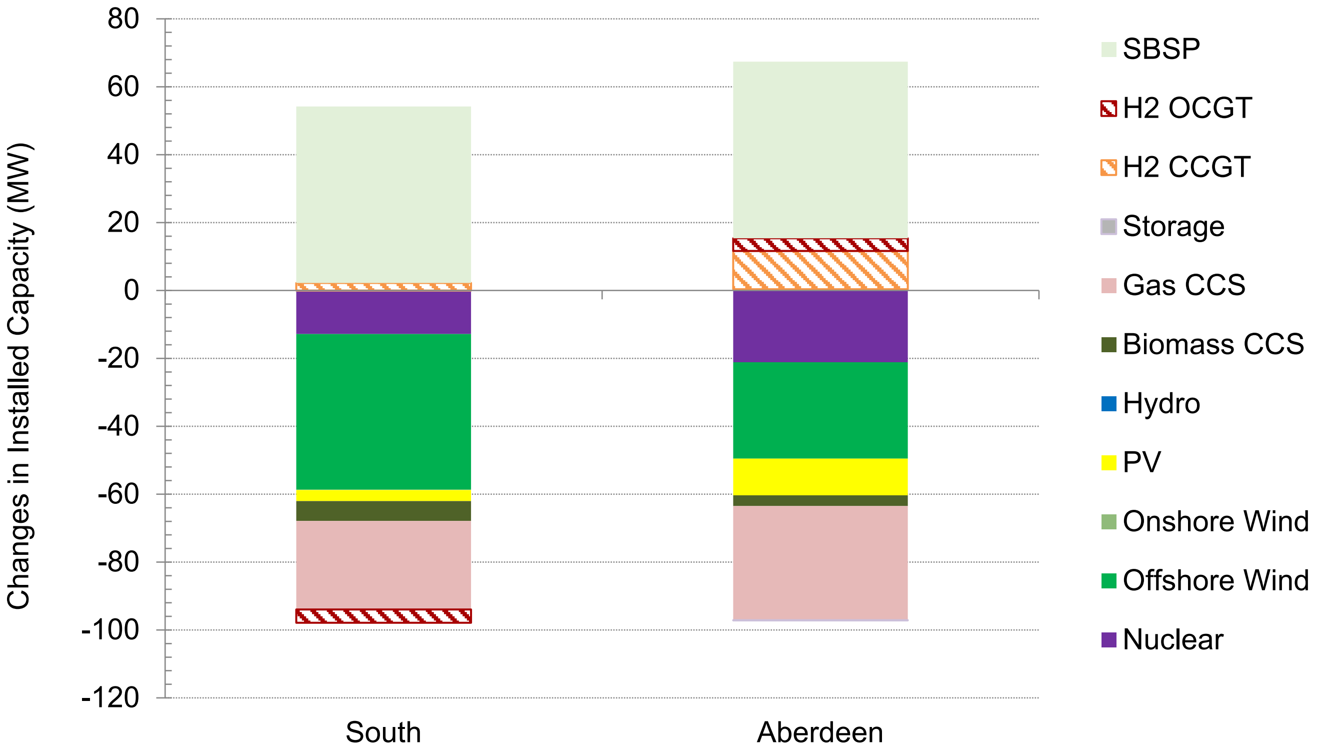
[47] Previous work by Imperial College London suggests that, beyond 1 GW, the energy system benefits of SBSP scale approximately linearly with capacity installed. It is possible that the marginal benefit of SBSP is constant or decreasing at the MW scale.

The majority of benefit stems from savings in the capital costs of displaced intermittent low-carbon technologies and lower energy system operating costs. Siting a rectenna in the south of England has several advantages. It reduces transmission congestion, enables the UK to export more electricity (via interconnectors) and, unlike the Aberdeen rectenna, does not increase hydrogen system costs.

Table 16 presents the lifetime benefits of a small-scale system configured for optimised utilisation under Scenario 3, from FOAK in 2030 to NOAK in 2040. Values are for the rectenna in the south of England.

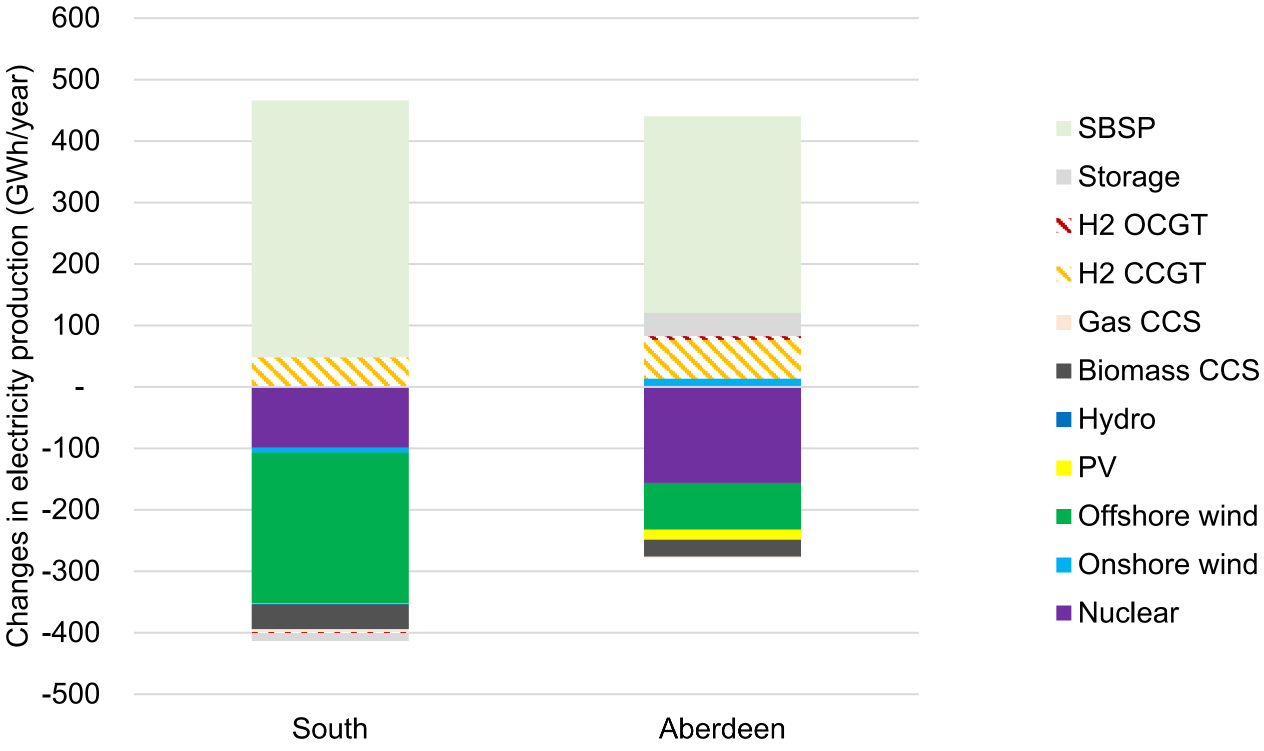
Parameter	2030	2035	2040
Small-scale SBSP capacity (MW)	31	42	52
Benefits per year (£ million)	13.6	18.4	22.8
Central baseline hurdle rate (%)	20.0	13.2	9.1
Lifetime benefits (£ million)	76.4	133	200

Figure 12 displays how 52MW of SBSP displaces a range of low-carbon technologies.



The high utilisation of SBSP under Scenario 3 compared to other low-carbon technologies means that SBSP is able to displace more capacity than it provides.

Figure 13 presents the impact that 52MW of SBSP has on the GB energy mix under Scenario 3.



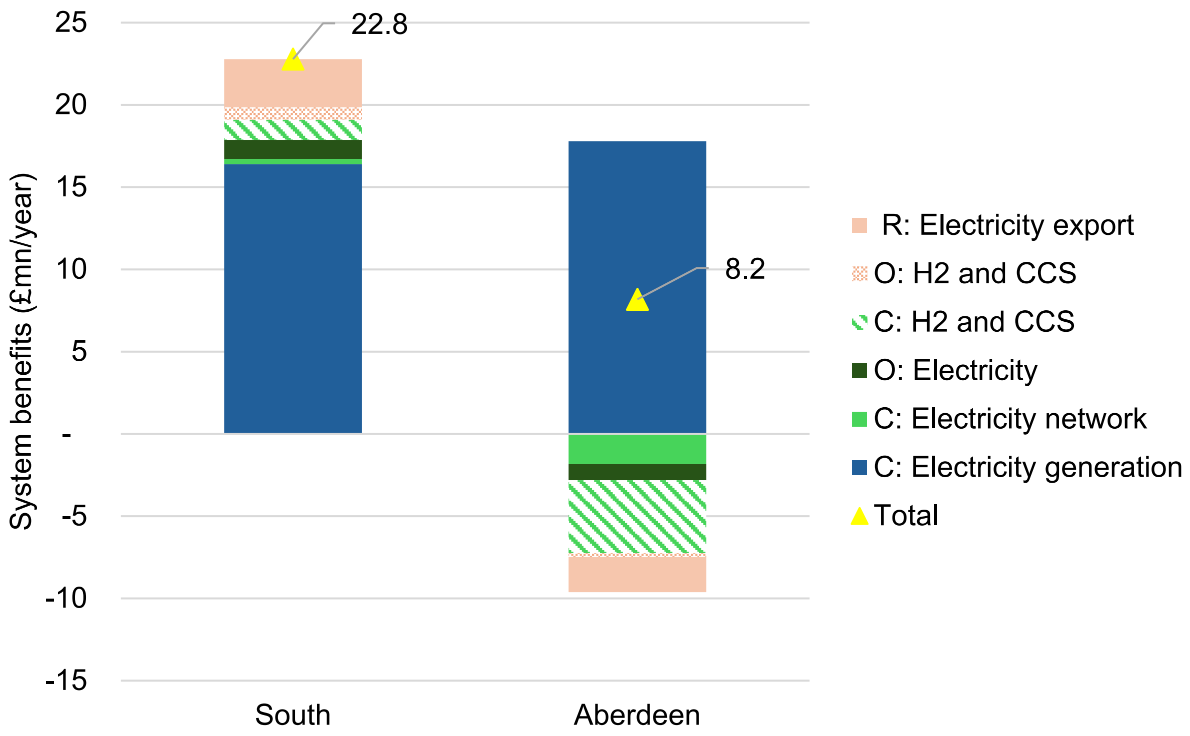
The changes in the energy mix highlight further differences between siting a rectenna in Aberdeen and in the south of England. Power from a rectenna in the south can be utilised 99% of the time, whereas use of a rectenna in Aberdeen is subject to transmission constraints, utilising only 75% of its potential. As a result, small-scale SBSP could displace a larger amount of existing capacity if the rectenna were sited in the south of England, compared to in Aberdeen. For similar reasons, a rectenna in the south would displace a more significant amount of offshore wind capacity, while a rectenna in Aberdeen would mostly displace nuclear generation.

Scenario 4 – Dawn/dusk optimisation

104 MW of SBSP—the capacity provided by a single NOAK constellation in 2040 under Scenario 4—is expected to generate energy system benefits of:

- £8.2 million per year if the rectenna is sited in Aberdeen.
- £22.8 million per year if the rectenna is sited in the south of England.

Figure 14 presents the energy system benefits associated with 104 MW of small-scale SBSP under Scenario 4 in the south of England and in Aberdeen.



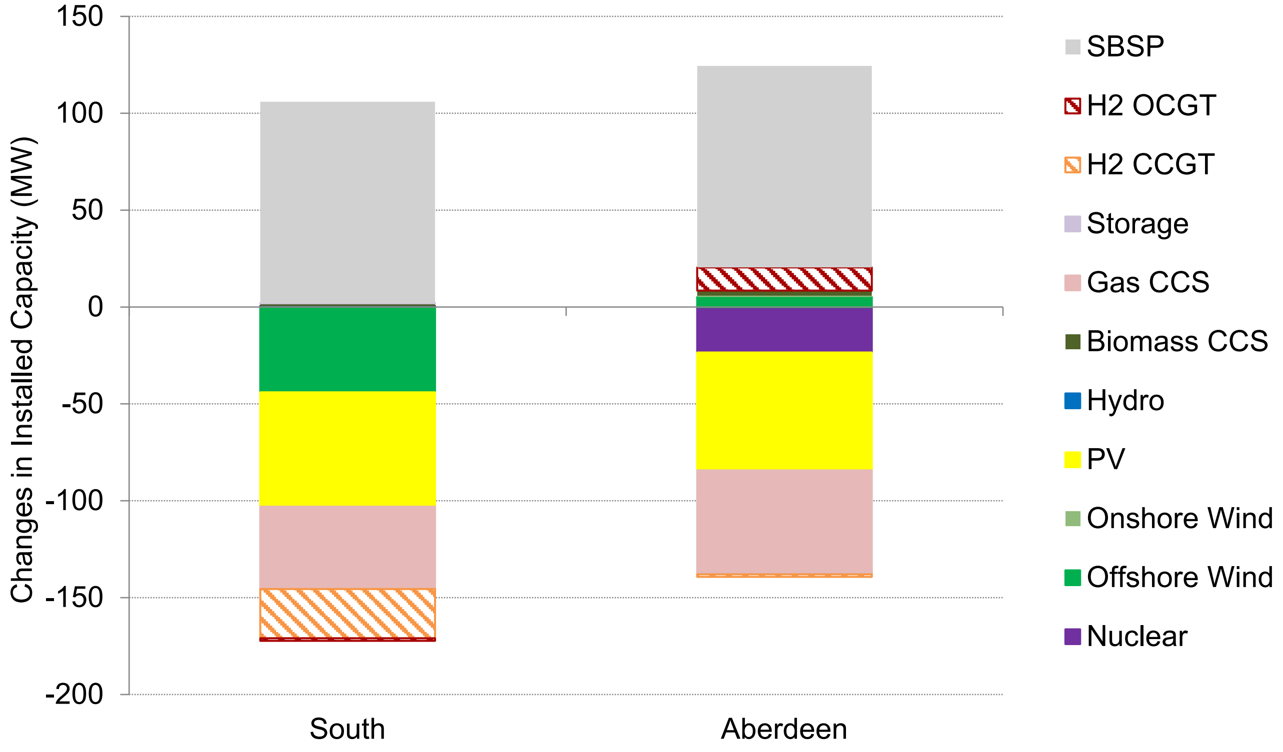
The majority of benefits stem from savings in the capital costs of displaced intermittent low-carbon technologies. Under Scenario 4, the benefits of SBSP are more sensitive to rectenna location than under Scenario 3. Intuitively, a rectenna in Aberdeen is often constrained (particularly at peak times), so investing in providing additional power to this location is less worthwhile. In contrast, the extra power provided to the south of England can be more fully utilised, leading to similar benefit as Scenario 3 (as Scenario 4 provides double the peak power).

Table 17 presents the lifetime benefits of a small-scale system configured for dawn/dusk under Scenario 4, from FOAK in 2030 to NOAK in 2040. Values are for the rectenna in the south of England.

Parameter	2030	2035	2040
Small-scale SBSP capacity (MW) (two satellites provide power at a time)	62	84	104
Benefits per year (£ million)	13.6	18.4	22.8
Central baseline hurdle rate (%)	20.0	13.2	9.1
Lifetime benefits (£ million)	76.2	133	200

If the rectenna is sited in the south, the system benefits associated with Scenario 4 are very close to the system benefits of Scenario 3. This implies the value of providing additional power at peak times almost entirely compensates for Scenario 4's lower utilisation.

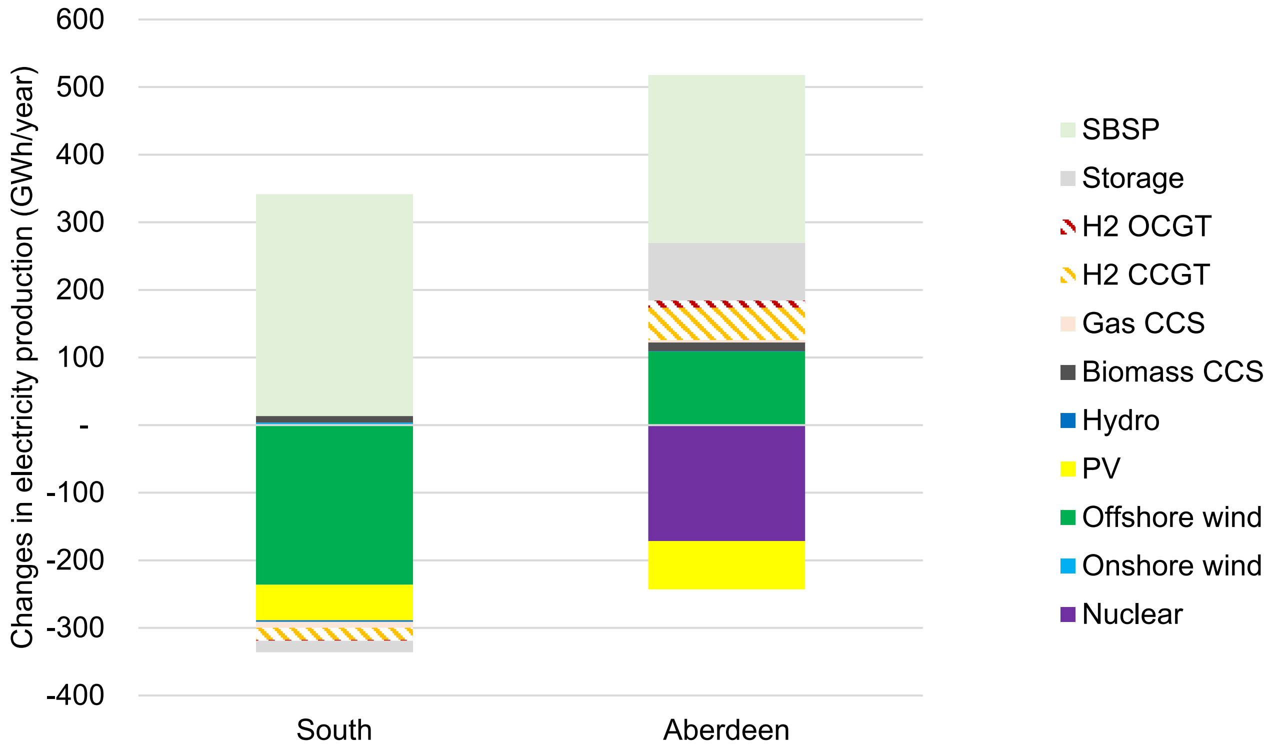
Figure 15 shows the extent to which 104 MW of SBSP displaces a range of low-carbon technologies under Scenario 4.



Scenario 4's reduced utilisation means the amount of capacity it displaces per GW is smaller. However, since Scenario 4 provides double the peak power of Scenario 3, the total displaced capacity is significantly more. Compared to Scenario 3, Scenario 4 displaces much more solar and gas CCS capacity, because it provides a larger amount of power during daytime hours.

Under Scenario 4, the differences between siting a rectenna in the south of England and in Aberdeen remain the same. A rectenna in the south displaces more offshore wind capacity and less nuclear.

Figure 16 presents the impact of 104 MW of SBSP on the GB energy mix under Scenario 4.



Under Scenario 4, power from a rectenna in the south can be utilised 98% of the time and a rectenna in Aberdeen can be utilised 74% of the time. A rectenna in the south displaces offshore wind and solar generation, while a rectenna in Aberdeen displaces nuclear and solar.

Energy system value-adjusted LCOE

Table 18 presents value-adjusted LCOE estimates based on Scenario 3 under the three baselines, calculated by subtracting expected savings in energy system costs from LCOE based on the whole energy system modelling above.

Baseline variation	2030 value-adjusted LCOE (£/MWh)	2035 value-adjusted LCOE (£/MWh)	2040 value-adjusted LCOE (£/MWh)
Optimistic	314	133	66
Central	519	210	101
Conservative	574	228	108

Supplementary funding

The LCOE and energy system benefits analysis considers economic value, which does not account for financial transfers between groups. However, it is possible that transfers, such as grant funding or temporary small commercial losses on the first small-scale system, would reduce the burden of support on the UK government. If grants are considered as a direct offset to capital costs, then the inclusion of grant funding reduces effective LCOE. For the first system in 2030, every £100 million received in grants reduces effective LCOE by £33.50.

Small-scale SBSP may be suited to grant funding because:

- Each milestone in the development roadmap provides technological spillovers to adjacent industries, including photovoltaics, wireless power transfer and in-orbit assembly. The benefit of developing SBSP systems is not internalised by the MVP manufacturer. In this case, government intervention (such as grant funding) might be suitable to encourage SBSP's development, unlocking benefits in other industries.
- Small-scale SBSP's ability to export power means that each constellation provides power to multiple nations, each of which may be willing to contribute funding towards a first small-scale system. This reduces the burden of funding on any one nation.

It is anticipated that a mix of private and public funding will support the first small-scale SBSP system. There is precedent, both in the UK and worldwide, for government support of cutting-edge energy projects. In the UK, Rolls-Royce SMR has received £210 million as part of Phase 2 of the Low-Cost Nuclear Challenge Project, administered by UKRI, which has been supplemented by £280 million of private capital.[48] Similarly, governments worldwide have committed $3.8 billion (£3 billion) alongside $2.4 billion (£1.9 billion) of private funding to support companies in exploring nuclear fusion concepts.[49] Further work is required to identify the specific public funding pools that are most compatible with small-scale SBSP worldwide. This will involve engagement with the UK government, as well as partner governments likely to receive power under the first system (Japan and Canada, in this study).

Financial feasibility

The financial feasibility assessment analyses the extent to which small-scale SBSP is:

- Compatible with UK government support under existing CfD precedents, and
- Commercially viable, so that the MVP manufacturer recovers its investment at the required hurdle rate.

Past CfD rounds do not determine ASPs in future rounds; each round is independent. In each round, the budget is set based on current policy, technology maturity and the market context. For the purpose of this assessment, small-scale SBSP is assumed to be financially feasible if its LCOE is such that it can be supported within the maximum ASP under CfD allocation round 6, accounting for energy system benefits and supplementary funding from outside the UK. In

[48] https://www.rolls-royce-smr.com/press/uk-poland-agreement-brings-rolls-royce-smrs-another-step-closer#:~:text=Rolls%2DRoyce%20SMR%20has%20received,%C2%A3280m%20of%20private%20capital

[49] https://www.nuclearbusiness-platform.com/media/insights/62-billion-fusion-energy-funding-race-turning-the-dream-of-creating-a-star-on-earth-into-reality.

practice, LCOE is just one of many inputs that determine strike prices. Other inputs excluded in this analysis include:

- CfD contract terms, including length, risk allocation and eligibility requirements.
- Other costs/benefits not included in LCOE or energy systems benefits modelling.
- Wider policy considerations.

Therefore, in practice, LCOE and strike prices may differ significantly, even after adjusting for energy system benefits. Financial feasibility, in this sense, is not an indication that the UK government should (or will) support small-scale SBSP at the maximum ASP. Rather, it places a reasonable bound on the level of support that may be possible, given historical CfD auction results. The maximum ASP was £261/MWh for tidal stream technologies in 2012 GBP, equivalent to £361/MWh in 2024 GBP. The assumed condition for financial feasibility is:

$$\text{CfD strike price } \leq \text{£}361/\text{MWh}$$

$$\text{CfD strike price} = \text{LCOE} - \text{energy system benefits} - \text{ supplementary funding}$$

Profit—revenue less costs—made by the MVP manufacturer must be at least zero:

$$(\text{CfD strike price} + \text{supplementary funding}) - \text{LCOE} \geq 0$$ [50]

Under these conditions, small-scale SBSP is financially feasible regardless of supplementary funding whenever the benefits-adjusted LCOE does not exceed £361/MWh. Small-scale SBSP is trivially commercially viable whenever LCOE is less than £361/MWh.

Table 19 presents the compatibility of small-scale SBSP with the CfD mechanism under the three baseline variations, accounting for energy systems benefits[51]

Baseline variation	2030 feasibility	2040 feasibility	2040 feasibility
Optimistic	CfD compatible	CfD compatible	CfD compatible
Central	£440 million funding required	CfD compatible	CfD compatible
Conservative	£602 million funding required	CfD compatible	CfD compatible

[50] For simplicity, it can be assumed that commercial actors can make losses for the first system in 2030, equivalent in magnitude to the energy systems benefits. In this case, the conditions for affordability and commercial viability are the same.
[51] In 2030, a £100 million reduction to overnight capital expenditure reduces LCOE by £33.50/MWh

Support costs under Scenario 3 and Scenario 4

Total support costs (expected to be a mix of public and private funding) are defined as follows.

$$\text{Total support costs} = \text{Supplementary funding} + \text{Lifetime expected CfD cost}$$

It is the funding required for a small-scale SBSP system that is not expected to be recovered by selling electricity at IMRP prices. For both Scenarios, the total support cost per MW of capacity and per MWh of electricity generated are calculated under the following assumptions:

- Lifetime CfD support costs, as a government investment, are discounted at the HM Treasury Green Book 3.5% rate,[52] and support costs are calculated for the **global** output of the system.
- Support costs are divided by total capacity (2024 GBP/MW) and lifetime global energy delivered (2024 GBP/MWh).[53]

It should be noted that this assessment does not account for business model-specific factors that are likely to affect support costs through LCOE and strike prices. Further explanation of these factors is provided in Annex A.

The LCOE of small-scale SBSP under Scenario 4 is higher than under Scenario 3 because Scenario 4 achieves lower average utilisation and requires double the number of rectennas, adding to capital costs. The value-adjusted LCOE of a small-scale SBSP system under Scenario 4 is £678/MWh in 2030 (FOAK), £288/MWh in 2035 and £150/MWh in 2040 (NOAK).

Table 20 presents the total public and private support costs for a small-scale SBSP system under Scenario 3 (with a load factor of 53.9%) and Scenario 4 (with a load factor of 48.8%).

Support cost	Scenario 3	Scenario 4
	2030 (FOAK)	
Total support per MW of capacity	£43.0 million	£26.6 million
Total support per MWh	£161	£218
	2035	
Total support per MW of capacity	£9.63 million	£5.80 million

52 The Green Book (2022) - GOV.UK
53 Support costs are divided by undiscounted lifetime electricity production so that the present value of total support costs can easily be calculated by multiplying support per MWh by lifetime electricity production (as specified for each Scenario in Chapter 3). Note that, if lifetime electricity costs were discounted, the estimated support costs would be significantly higher: 2.67 times higher in 2030; 2.06 times higher in 2035; and 1.71 times higher in 2040. While useful, these values would exaggerate support costs, because support is discounted at the Green Book rate, which is much lower than hurdle rates.

Total support per MWh	£35.7	£48.3
2040 (NOAK)		
Total support per MW of capacity	£1.5 million	£1.5 million
Total support per MWh	£5.38	£12.1

7. Conclusions

This section provides the study's conclusions.

This study set out to understand whether small-scale SBSP could support the UK on a pathway to Net Zero by providing efficient, economically competitive and low carbon power in the 2030s. It finds that small-scale SBSP provides a promising option for the UK, which is likely to become economically competitive by 2040. It also de-risks the development of a large-scale SBSP system.

The unique properties of small-scale SBSP (high load factor, non-intermittent, predictable and flexible) are likely to enable it to support the UK's Net Zero ambitions in a way that complements existing low-carbon technologies. The energy system modelling suggests that the introduction of small-scale SBSP could avoid overbuild of renewable generators if the rectenna is installed in the south of England. This would reduce the need for expensive, dispatchable terrestrial generators in adverse weather and would reduce the UK's reliance on conventional energy sources, such as gas (with carbon capture and storage) and nuclear, reducing electricity costs during peak demand.

The estimated LCOE of a small-scale SBSP system is £335-595/MWh in 2030 (FOAK), £154-249/MWh in 2035 and £87-129/MWh in 2040 (NOAK). While there remains significant uncertainty in key parameters (such as launch cost, lifetime and hurdle rate), central estimates suggest that small-scale SBSP is likely to be cost-competitive with nuclear power and tidal stream technologies by 2040 (NOAK). While it is likely that the first small-scale system in 2030 will require significant public and private support, this support is likely to fall for a 2035 installation and may be negligible by 2040 (NOAK).

Additionally, small-scale SBSP is expected to accelerate the technological development of and, crucially, de-risk the implementation of large-scale SBSP systems. This de-risking effect has the potential to reduce the LCOE of a large-scale SBSP system by between 16% and 27%, increasing its competitiveness and reducing the barriers to realising SBSP's full potential.

Further work is required to increase the robustness of these findings and ensure small-scale SBSP is a value for money investment. Potential further work could:

- Continue to identify and resolve the technical barriers associated with deploying SBSP in the 2030s.
- Define the key specifications of a small-scale SBSP system in more detail, including the system design, UK-serving orbit and concept of operations. This may require engagement with key dependencies, such as providers of launch vehicles.
- Update and fully specify a bottom-up cost model to increase confidence in small-scale SBSP's economic viability. A similar updated model could also be produced for large-scale SBSP to reflect the substantial development since Frazer-Nash's 2021 study. This

would reduce the risk associated with achieving the predicted return on investment, making a 2030 deployment more achievable.

- Provide a full micro-scale in-orbit demonstration of SBSP ahead of the implementation of small-scale SBSP, de-risking the small-scale system and enabling the efficacy of key systems to be evaluated.

8. Annex A: LCOE modelling

Annex A lays out the methodology for estimating levelised cost of electricity (LCOE). It explains the form of the model, lays out input value assumptions and details the sensitivity analysis.

The purpose of LCOE, strike prices, and Space Solar's view

Considering financial and business model-specific factors and using different assumptions to the modelling in this report, Space Solar believe a FOAK small-scale SBSP system could provide electricity at a strike price between £182/MWh and £255/MWh.

This study calculates LCOE in a way that reflects the primary function of LCOE for the UK government: to compare the relative cost of different electricity generation technologies. It is a high-level economic metric that does not account for business model-specific factors that may affect the cost at which Space Solar could supply electricity to the GB grid.

Space Solar has conducted its own modelling with different underlying assumptions in which LCOE serves a different purpose: it represents the price at which Space Solar believe electricity would need to be provided under their technical assumptions and business model. **The difference in LCOE's purpose means that this study neither validates nor refutes Space Solar's modelling**. A key difference is that Space Solar's business model does not propose that technology and construction risks are carried by investors in the individual systems. Rather, such investors are proposed to fund completed operational systems with output guarantees, releasing the capital back to construct the next systems. This approach subsumes technical and construction risks into the overall development cost to be recovered by Space Solar's direct investors (venture and eventually public markets) across hundreds of future systems. As such Space Solar believes the FOAK small-scale SBSP system will face a lower hurdle rate than the rate assumed in this study; between 8% and 14.9%, reducing thereafter in subsequent systems.

Additionally, alongside the factors explained on pages 46-47, there may be business model-specific factors that mean strike prices and LCOE are different. Space Solar's modelling accounts for business model-specific factors and uses less conservative assumptions about hurdle rate launch cost (£772/kg to LEO). As a result, Space Solar believe a FOAK small-scale SBSP could be delivered at a strike price in the range of £182/MWh to £255/MWh, assuming the capital expenditure is fully privately funded.

Model overview

The approach to modelling LCOE is tailored to the context of the study. Small-scale SBSP has not yet been built, launched or fully demonstrated and, as such, there are significant technical and economic uncertainties that have a large impact on calculated LCOE. This means that, to be effective, the LCOE model must:

- Capture and utilise uncertainty to make meaningful predictions and outputs.
- Enable scenario modelling and sensitivity analysis to understand the drivers of the results.

A Bayesian network LCOE model fulfils these requirements. A Bayesian network is a statistical technique that can be used to capture a range of inputs (either data or expert judgements), while providing an efficient way of making meaningful projections where there are significant unknowns. Bayesian networks are composed of nodes and edges. Nodes denote input and output variables and are represented within the model using probability distributions. Edges represent directionally dependent, mathematically defined relationships between nodes. They link input nodes to intermediate nodes, and intermediate nodes to output nodes. Within this model formulation, nodes are represented using probability distributions that capture the spread of all anticipated eventualities and their corresponding likelihoods. By incorporating probabilistic relationships, Bayesian models can rapidly analyse uncertainties using variance-based sensitivity (Sobol) analysis, leading to an understanding of the most significant drivers of uncertainty in LCOE.

In this model, inputs are either:

- Constant.
- Uniformly distributed.
- Normally distributed.

Since no historical data is available, the uncertainty assigned to each input is either a judgement or is based on the variance of future projections from various sources.

LCOE measures the average net present cost of electricity generation over the lifetime of an asset. For ease of computation within the Bayesian framework, LCOE is approximated by simple LCOE, (sLCOE) in this model. This approximation is exact when annual operating costs and electricity generation are constant over the asset's lifetime, and complex factors such as financial constraints and asset degradation are absent. In this case, these assumptions are likely to be reasonable: operational costs and generation for a given small-scale SBSP system should not change year to year. Degradation in photovoltaic performance (which is assumed to be linear) does reduce energy generation over the lifetime. This is compensated for using the average photovoltaic performance over the lifetime. SBSP only incurs fixed, and not variable (per MWh), operational costs, and there is no fuel cost, so sLCOE is given by the following equation.[54]

$$\text{sLCOE} = \frac{\text{Capex} \times \text{CRF} + \text{Fixed O\&M}}{8760 \times \text{CF}}$$

Capex is the present value of all capital costs, including production of the satellite and rectenna, and launch costs, **on a £ per MW basis**. Fixed O&M is the set of operational and maintenance costs each year that do not depend on electricity output, **on a £ per MW per year basis**. The capital recovery factor (CRF) is the proportion of Capex that must be recovered each year for a given hurdle rate and a given asset lifetime. The capacity factor (CF) provides an adjustment based on the proportion of the year that the asset is generating electricity. The number of hours in a year—8760—provides conversion from power to energy, in MWh. LCOE is measured in £ per MWh.

Model specification

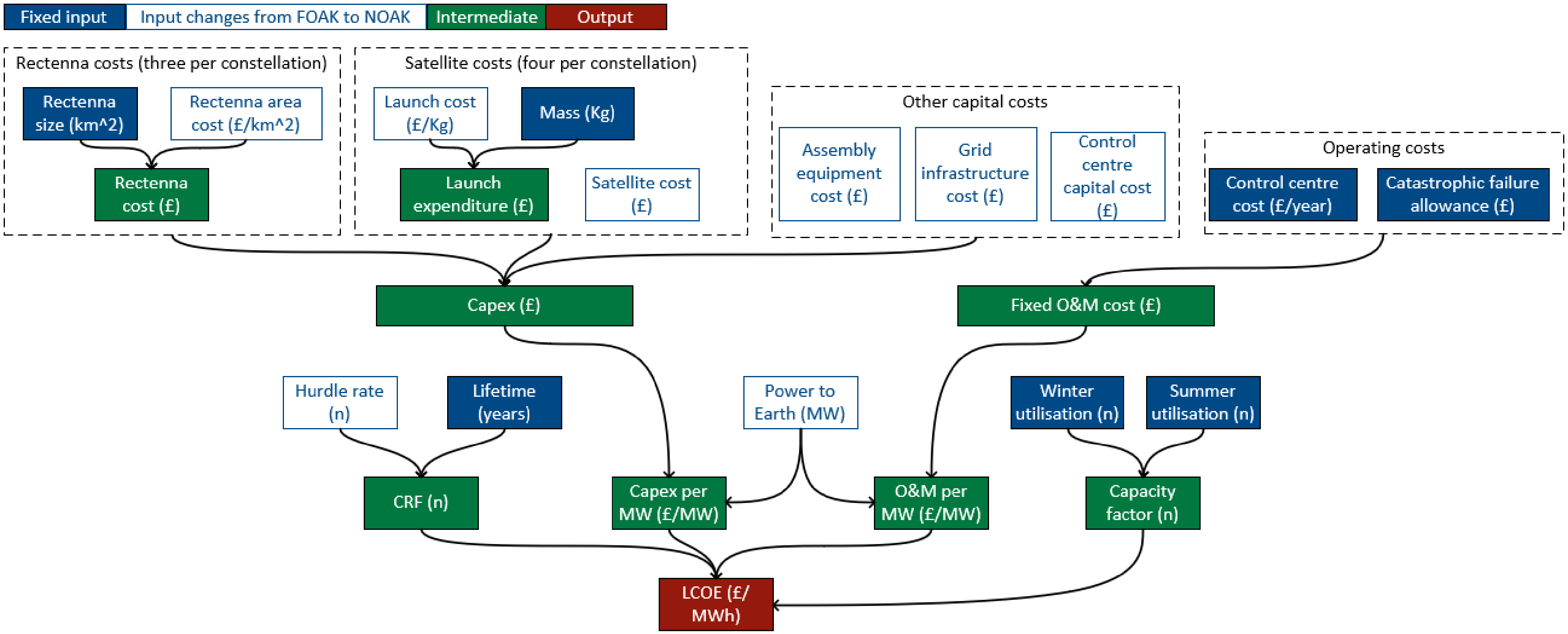
The LCOE model is specified to consider **global** electricity generation over the lifetime of the asset. This includes power to the UK and the exported power delivered to other countries.

As a result, the power delivered by a system of four satellites is given as the sum of the power delivered by each satellite (124MW in 2030). The Capacity Factor is the average utilisation of each satellite in the constellation.

[54] Further detail on sLCOE is provided by NREL here. The methodology is also aligned to the NASA Space Based Solar Power report (2024).

Model specification

The model is specified to capture the input data available for the MVP solution. **Figure 17 provides the model in full.** Note that the model is unable to calculate solar panel degradation directly; instead, the outputs are adjusted outside of the model to account for this.



The model's nodes are governed by the relationships in Table 21.

Ref	Node description	Units	Equation	Equation source
[1]	Launch cost per kg	£/kg	-	-
[2]	Mass	kg	-	-
[3]	Launch expenditure	£	$[1] \times [2] \times [4]$	-
[4]	Number of satellites	n	-	-
[5]	Number of rectenna	n	-	-
[6]	Satellite build cost, each	£	-	-
[7]	Satellite build cost, total	£	$[4] \times [6]$	-
[8]	Other Capex	£	-	-
[9]	Rectenna size	km^2	-	-
[10]	Rectenna cost, per unit area	£/km^2	-	-
[11]	Rectenna cost, total	£	$[5] \times [9] \times [10]$	-
[12]	Control centre operating cost	n	-	-
[13]	Catastrophic failure allowance	n	-	-
[14]	Capex	£	$[3] + [7] + [8] + [11]$	-

[15]	Fixed Operation & Maintenance (O&M)	£/year	$[14] \times ([12] + [13])$	-
[16]	Power to Earth	MW	-	-
[17]	Winter utilisation	n	-	-
[18]	Summer utilisation	n	-	-
[19]	Hurdle rate	n	-	-
[20]	Lifetime	Years	-	-
[21]	Capex per MW	£/MW	$\frac{[14]}{[16]}$	-
[22]	Fixed O&M per MW	£/MW/year	$\frac{[15]}{[16]}$	-
[23]	Capacity factor	n	$\frac{[17] + [18]}{2}$	-
[24]	CRF	n	$\frac{[19] \times (1 + [19])^{[20]}}{(1 + [19])^{[20]} - 1}$	NREL[55]
[25]	LCOE	£/MWh	$\frac{[21] \times [24] + [22]}{8760 \times [23]}$	NREL[55]

[55] NREL: Simple LCOE Calculator Documentation

Model inputs

This section provides justification for the model's input values. Detailed justification is provided for key inputs, including launch costs, satellite build costs and performance, rectenna costs and hurdle rate. Since the model is run for 2030, 2035, and 2040, this section also provides the rationale for the evolution of inputs values across these dates.

Inflation and exchange rates

All monetary inputs into the model are given in 2024 GBP. Where input data is found in a different currency, it is inflated to 2024 prices. Then it is converted to GBP using the 2024 average exchange rate, for instance £1 = $1.2781.[56] The CPIH—consumer price index including owner occupiers' housing costs—is used to adjust values to 2024 prices as required.[57]

Some inputs values are highly uncertain and can be estimated through different procedures or with different levels of optimism bias adjustment. For these inputs, up to three approaches are considered: an optimistic approach, a medium approach and a conservative approach. The study's baseline case uses medium estimates (or conservative where a medium approach is not specified). Therefore, the study's baseline can be seen as a mildly conservative interpretation of small-scale SBSP's costs and technical performance.

Launch costs

Launch costs are based on the anticipated specifications of SpaceX's upcoming Starship super-heavy launch vehicle. Starship is expected to be commercially operational by 2030, having signed a commercial contract to deliver cargo to LEO from 2028.[58] The calculation of launch cost in the model is defined by two key assumptions:

- Starship will provide at least 100 tonnes of launch capacity to LEO, and the SBSP satellite will be able to use this without encountering other constraints (i.e. volume limitations).
- The cost of launching a Starship to LEO.

Due to the substantial uncertainty around Starship launch costs, two approaches are considered:

- **An optimistic approach.** The cost of launching one Starship to LEO in 2030 is assumed to be the same as the cost of launching SpaceX's Falcon Heavy launch vehicle, $101 million (£79 million).[59] The cost to launch a Starship is assumed to fall

[56] GBP: USD exchange rate.
[57] CPIH INDEX 00: ALL ITEMS 2015=100 - Office for National Statistics
[58] Space X signed a contract in January 2024 to deliver Starlab's commercial space station to LEO in 2028 using Starship.
[59] Cost of $97 million provided by SpaceX in 2022. The cost is not provided for 2024. The cost has been inflated to 2024 prices using a proportional increase in line with Falcon 9, which has a price provided for both dates.

linearly until 2040, when it is the same as the cost of Falcon 9, $69.75 million (£55 million).

- **A conservative approach.** The cost of launching one Starship to LEO in 2030 is assumed to be $140 million (£110 million), following the base case assumption employed by London Economics in a 2024 analysis.[60] This value is significantly higher than Space X's launch cost targets, reflecting SpaceX's substantial market power and recent supply chain issues. The cost to launch a Starship is expected to fall as supply increases throughout the 2030s and new heavy launch vehicles (e.g. Blue Origin New Glenn) diminish SpaceX's market position. For approximate consistency across approaches, costs are assumed to fall linearly 30% from 2030 to 2040.

Cost to reach LEO

Launch costs per kg to LEO under the optimistic approach are:

- $\frac{\pounds 79\ million}{100\ tonnes}$ = £790 per kg **in 2030**
- $\frac{\pounds 67\ million}{100\ tonnes}$ = £670 per kg **in 2035**
- $\frac{\pounds 55\ million}{100\ tonnes}$ = £550 per kg **in 2040**

Under the conservative approach, launch costs to LEO are:

- $\frac{\pounds 110\ million}{100\ tonnes}$ = £1100 per kg **in 2030**
- $\frac{\pounds 67\ million}{100\ tonnes}$ = £935 per kg **in 2035**
- $\frac{\pounds 55\ million}{100\ tonnes}$ = £770 per kg **in 2040**

Cost to reach the desired HEO

The MVP solution is designed to orbit in a highly elliptical 556 km x 7,821 km orbit at 116.6-degrees of inclination (63.4-degrees from 180/0-degrees). Starship's capabilities are currently uncertain. It could reach the desired orbit by:

1. Delivering the payload to LEO
2. Refuelling in LEO by docking to a refuelling depot
3. Delivering the payload from LEO to the desired HEO

It also might be capable of direct delivery to HEO. Calculating costs to HEO by refuelling requires a large number of speculative assumptions. Instead, launch costs are estimated for a

[60] Disruptive launch and the shift from a mass to a cost paradigm in satellite communications, London Economics (2024)

direct transfer to HEO, using performance information for Space X's Falcon 9 and Falcon Heavy launch vehicles. This process is applied to the optimistic approach as follows:

1. The relative performance of Falcon 9 and Falcon Heavy is estimated by the ratio of payload mass that each can transfer to geostationary transfer orbit (GTO).
    a. Falcon 9 can transport 4,536 kg to GTO at a 28.5-degree inclination. [61]
    b. Falcon Heavy can transport 26,700 kg to GTO at a 27-degree inclination.[62]
2. The mass Falcon 9 can transport to a 500 km x 10,000 km orbit at a 60-degree inclination is estimated. This orbit is used as a proxy for the desired HEO.
    a. At a 28.5-degree inclination, Falcon 9 can transport 9,727 kg to a circular 500 km LEO orbit and 7,000 kg to a 500 km x 10,000 km orbit.[61]
    b. At a 60-degree inclination, Falcon 9 can transport 8,948 kg to a circular 500 km LEO orbit.[61] Assuming the circularisation factor is the same as in a), this implies Falcon 9 can transport $\frac{7{,}000}{9{,}727} \times 8{,}948 = 6{,}439$ kg to a 500 km x 10,000 km orbit at 60-degrees of inclination.
3. The relative performance of Falcon 9 and Falcon Heavy is used to estimate the payload Falcon Heavy can deliver to the proxy orbit.
    a. $\frac{26{,}700}{4{,}536} \times 6{,}439 = 37{,}904$ kg
4. The performance and cost data of Falcon Heavy and Starship are related such that the assumptions are equivalent to the LEO cost estimation.
    a. Falcon Heavy costs £79 million to launch. It is estimated to be able to deliver a payload of 37,904 kg to the proxy orbit, yielding a cost per kg of $\frac{£79\ million}{37{,}904}$ = £2,084.
    b. Similarly, Falcon Heavy can deliver 57,000 kg to LEO in reusable mode,[62] yielding a cost per kg of $\frac{£79\ million}{57{,}000}$ = £1,386.
    c. Assuming the launch cost per kg ratio between Falcon Heavy and Starship is the same for deliveries to the proxy orbit and to LEO, the estimated cost of Starship to the proxy orbit is $\frac{£790}{£1{,}386} \times £2{,}084$ = £1,188.

Then, assuming costs to the proxy orbit and the desired HEO orbit are the same, and using the same cost progression as for the LEO case, costs under the **optimistic approach** are as follows:

- £1,188 per kg **in 2030**

[61] Value taken from the original SpaceX Falcon 9 User's Guide
[62] Value taken from the Falcon Heavy Wikipedia page

- $\frac{£670}{£790} \times £1{,}188$ = £1,008 per kg **in 2035**
- $\frac{£550}{£790} \times £1{,}188$ = £827 per kg **in 2040**

Assuming the cost ratio between LEO and the target orbit are the same for both approaches in 2030, launch costs under the **conservative approach** are:

- $\frac{£1{,}100}{£790} \times £1{,}188$ = £1,647 per kg **in 2030**
- $0.85 \times £1{,}647$ = £1,400 per kg **in 2035**
- $0.7 \times £1{,}647$ = £1,153 per kg **in 2040**

Satellite build costs and performance

The cost to build each small-scale SBSP satellite is provided by Space Solar's financial model. The model projects a FOAK build cost of £68.5m per satellite. Compared to other satellites, this is extremely competitive on a cost per kilogram basis. For instance, a typical GEO communications satellite with a mass of 2,500 kilograms might cost $150 million (£117 million) to build.[63] Thus we have:

- FOAK small-scale SBSP: $\frac{£68.5\text{m}}{88{,}000} = £780/\text{kg}$
- NOAK GEO communications satellite: $\frac{£117\text{m}}{2{,}500} = £46{,}800/\text{kg}$

The difference in cost is attributable to the hyper-modular nature the CASSIOPeiA design, enabling satellite components to be mass-produced instead of bespoke. SpaceX's Starlink satellites, which have been mass-produced to the order of thousands of units, provide a relevant comparison. Estimated costs per kilogram are as follows:[64]

- Starlink V1 satellites cost $200,000 (£156,000): $\frac{£156{,}000}{260} = £600/\text{kg}$
- Starlink V2-mini satellites cost $800,000 (£626,000): $\frac{£626{,}000}{730} = £858/\text{kg}$
- Starlink V3 satellites are forecast to cost $1.2m (£939,000): $\frac{£939{,}000}{1{,}500} = £626/\text{kg}$

It is likely that a FOAK small-scale SBSP satellite would be more expensive than Starlink because of the more substantial structural requirements of a larger satellite, and Starlink's status as a NOAK product. Different input variations are developed by applying an optimism bias. In line with HM Treasury Green Book guidance, an optimism bias between 10% and 200% can be applied on equipment or development project. Three approaches are considered for 2030:

- **Optimistic approach:** Optimism bias is not applied, so FOAK build cost is £68.5m per satellite.

[63] Space on Budget - Armada International
[64] Starlink soars: SpaceX's satellite internet surprises analysts with $6.6 billion revenue projection - SpaceNews

- **Central approach:** An optimism bias of 50% is applied, so FOAK build cost is £103m per satellite.
- **Conservative approach:** An optimism bias of 100% is applied, so FOAK build cost is £137m per satellite.

The cost of each satellite is expected to fall throughout the 2030s by two mechanisms:

- Cost reductions from manufacturing scale efficiencies.
- Cost reductions from the introduction of new generations of modules with more advanced, cheaper and lighter technologies.

Manufacturing scale

Each satellite is composed of around 7,000 modules. As such, it is assumed that modules will be mass-produced from the first constellation (which relies on a sufficient demand signal to put necessary infrastructure in place). Learning-by-doing is expected to drive process improvements that enable cost reductions as scale is achieved. The magnitude of these manufacturing scale cost reductions is estimated using the Wright learning rate model. The Wright model supposes that as production scale doubles, costs per unit fall by a fixed factor. This factor is called the learning rate, expressed as a percentage of the original cost. A lower percentage means a higher cost reduction as production volume increases.

A significant body of literature exists estimating the learning rates in various industries. Learning rates tend to be between 65% and 100%, with 82% being the most common learning rate across industries. The most common learning rate used for aerospace is 85%, which implies that cost per unit falls to 85% of its original value as production scale doubles.[65] The learning rate applied for small-scale SBSP is 90%, which can be seen as moderate to conservative.

Table 22 provides the estimated scale of total SBSP production throughout the 2030s. It should be noted that these values indicate the estimated maximum production capacity, assuming demand for SBSP products is unconstrained. Additionally, small-scale SBSP benefits from all production under the CASSIOPeiA design, whether it is for the small-scale product or otherwise.

Year	Cumulative scale (tonnes)	Wright's law – cost change factor
2030	352	1
2035	1,104	0.777
2040	8,716	0.578

65 Learning Rate Sensitivity Model, Brown (2018)

Generational improvements

Generational improvements are another, separate driver of cost reductions throughout the 2030s. Each generation of satellites is assumed to be more mass efficient, that is, each module in the satellite can produce the same power as the previous generation, but with less mass. Importantly, this improvement is assumed to have a **double** benefit:

1. The satellite is sized to be as large as possible while fitting on a single Starship. If each module's mass is lower, then more modules can fit on a single Starship launch at the same total satellite mass, increasing the power output of each satellite. Adding more modules is assumed to not increase total cost because each module is lighter, and it is assumed that build cost scales linearly with module mass. This implies the more mass-efficient modules are no more complex or costly to produce.
2. The more modules on each satellite, the larger the effective transmission aperture. The larger the aperture, the smaller the energy beam's diameter on the ground, and the more intense the energy (in terms of W/m^2). A more intense, compact energy beam can transmit a larger proportion of collected energy to the rectenna, increasing the efficiency of the system.

Additionally, and separately, each generation is assumed to be cheaper on a £/kg basis. This improvement is expected to arise from two factors:

- **Design.** The design will be adjusted for easier/more efficient manufacturability and less material waste. This improvement will be enabled by learning-by-doing.
- **Component costs**. Each successive generation is expected to make use of cheaper components, such as semiconductors.

Table 23 provides Space Solar's forecast for generational improvements, relative to the previous generation.

Generation #	Technical improvement	Cost improvement	Year of introduction
1 (FOAK)	-	-	2029
2	12.5%	12.5%	2032
3	12.5%	12.5%	2035
4	10%	10%	2038
5 (NOAK)	5%	5%	2040

Finally, Space Solar assumes that assembly equipment will also become lighter from 2030 to 2040, leaving additional space in a single Starship launch for satellite modules. The mass of assembly equipment is assumed to fall linearly from 10 tonnes in 2030 to 7.5 tonnes in 2040. Limited evidence is available in support or against this assertion, so it is taken forward.

Table 24 provides the progression of key metrics in 2035 and 2040 from the baseline in 2030.

Year	Technical improvement					Cost improvement		
	Module generation - W/kg change factor	Transmission efficiency	Mass available for power-generating modules	Total power delivered to Earth – MW change factor	Cumulative scale to date (tonnes)	Wright's law - £/kg change factor	Module generation - £/kg change factor	Total £/kg change factor
2030	1	45%	88	1	352	1	1	-
2035	1.266	48%	89	1.37	1104	0.777	0.766	0.595
2040	1.462	51%	90	1.69	8716	0.578	0.654	0.378

The implication of these assumed cost and performance improvement rates under the **medium approach** is as follows:

- **In 2030**, each satellite costs £103 million to build and is capable of delivering 31MW to the ground.
- **In 2035**, each satellite costs £61.1 million to build and is capable of delivering 42MW to the ground.
- **In 2040**, each satellite costs £38.9 million to build and is capable of delivering 52MW to the ground.

Rectenna costs

Rectenna costs are composed of the cost of building the rectenna, and the cost to use the land the rectenna sits on. Rectenna build costs depend on three factors: the number of rectennas required, the size of each rectenna and the cost per unit size. It is assumed that:

- For each constellation, three new rectennas will be required (under Scenario 3). The first constellation has been modelled as having rectennas in Aberdeen (UK), Edmonton (Canada) and Sapporo (Japan), which enables high utilisation and export revenues.
- The rectenna is sized to capture the first minimum of the RF beam of a 2040-spec satellite. If the satellite were stationary in the sky and the rectenna were at the same latitude as the satellite, then the rectenna would need to be 3.1 km^2 to capture the first minimum. However, the satellite moves longitudinally across the sky and projects from a lower latitude than the rectenna—both these factors 'stretch' the beam, making the first minimum larger. Space Solar suggests applying 30-degrees of stretch in both directions accounts for this appropriately. Under this assumption, the required size of the rectenna is calculated as 13.4 km^2.

Rectenna build costs per unit area are assumed to follow Wright's law. No specific learning rate analysis has been undertaken in advance of this study, so a moderate learning rate—95%—has been applied.[65] This is designed to reflect the relative simplicity and maturity of the components of rectenna technology, compared to the satellite.

Table 25 presents the implications of this learning rate for rectenna costs per square metre.

Year	Cumulative scale (km^2)	Cost (£/m^2)
2030	40.2	6.90
2035	208	6.11
2040	1293	5.34

The land right of use (RoU) cost is estimated using two assumptions:

- As a reasonable worst case, the average value of UK arable land and pastureland is used, which is $\frac{£9,722+£7,889}{2}$ = £8,806 per acre as of the end of 2024.[66]
- It is assumed that the cost of a 30-year RoU would be 50% of the land purchase value.

This implies a land RoU cost of £1.09 per square metre. This means total rectenna cost is:

- £7.99 per square metre in **2030.**
- £7.20 per square metre in **2035.**

[66] Carter Jonas: Farmland Market Update Q4 2024

- £6.43 per square metre in **2040.**

Hurdle rate

The hurdle rate is the minimum required rate of return for the construction of a small-scale SBSP constellation to be commercially feasible. Investors need to be compensated for taking risk, so the hurdle rate increases when the investment is riskier. Funding the first constellation will be highly risky, so investors will require a large return. Then, as the technology is proven and scale is increased, it is assumed that the risk associated with subsequent constellations will fall. In practice, this means new groups of investors, with a lower appetite for risk but also a lower required return, would begin to fund small-scale SBSP.

Benchmark: Hurdle rates of comparable FOAK generation technologies

Gas carbon capture and storage (CCS): The estimated hurdle rate for a FOAK gas CCS generator is 12%-17% for a plant commissioned in 2010 and 9% for a plant commissioned in 2018. A NOAK CCS gas generator commissioned in 2018 has an estimated hurdle rate of 7.1%.[67]

Tidal stream: The hurdle rate of deep tidal stream generation was estimated to be between 10.8% and 14.8% in 2015. The estimated hurdle rate for a plant commissioned in 2018 is 9%.[68]

Two approaches have been adopted for hurdle rates.

- **An optimistic approach.** This follows capital structure modelling, assuming the perceived risk of small-scale SBSP is sufficiently low to access existing infrastructure funds. The rationale for this approach is that, compared to a large-scale system, small-scale SBSP is less complex and so the hurdle rate should be lower.
- **A conservative approach.** This retains the 20% FOAK hurdle rate used in past studies of large-scale SBSP. This value scales throughout the 2030s at the same rate as in the optimistic approach.

Under the **optimistic approach**, the evolution of the hurdle rate is modelled as a set of capital structures that become ‘unlocked’ when certain maturity conditions are met. The first constellation will be funded through an initial capital structure, with investment provided through private markets (e.g. private equity). Note that this approach, while quantitatively sound, does not address fundamental differences between SBSP and conventional infrastructure, particularly in terms of technology and regulatory risks.

[67] 2010 high and low estimates (Oxera, 2011); 2018 estimate (BEIS, 2016)
[68] 2015 high and low estimates (NERA, 2015); 2018 estimate (BEIS, 2016)

Terminology: infrastructure asset classification [69]

Core infrastructure is the set of assets that sit in a developed market with low demand risk and mature economic regulation. The core classification covers most business-as-usual infrastructure assets, including water, electricity and gas networks, and rail.

Core + infrastructure carries some market risk. However, the market has some features that mitigate this risk, such as high barriers to entry or long-term government support schemes (e.g. contracts for difference). The Core + class includes renewable energy assets such as offshore wind farms.

Core ++ infrastructure carries a higher level of market risk than Core +. Core ++ includes assets in highly competitive markets with demand volatility, and assets in emerging markets with developing economic regulation.

The subsequent capital structures are:

- **Crossover funds** – investment funds that invest in both publicly owned and private investments. This capital structure is assumed to be unlocked after the first constellation is operational.
- **Core ++ infrastructure funds –** this capital structure is assumed to be unlocked when the technology has been proven in operation for five years.
- **Core + infrastructure funds -** the final capital structure is unlocked when the technology has been proven in operation for ten years.

Hurdle rates are estimated using weighted average cost of capital. Each subsequently unlocked capital structure has:

- A lower cost of equity (and debt), as funds with a lower required return are used
- A higher proportion of debt, and less equity.

Both factors contribute to the fall in hurdle rate.

Table 26 provides the estimated hurdle rates associated with each capital structure.

#	Capital structure description	Real pre-tax hurdle rate	Year unlocked
1	Private markets / Private equity	14.9%	2030
2	Crossover funds	9.8%	2031
3	Core ++ infrastructure	6.75%	2036

[69] Definitions provided by Linklaters: Growth of non-core infrastructure (2018)

4	Core + infrastructure	4.83%	2041

Under the **optimistic** approach, hurdle rates are assumed to be 14.9% in 2030, 9.8% in 2035 and 6.75% in 2040. Under the **conservative** approach, hurdle rates are assumed to be 20% in 2030, scaling at the same rate to 13.2% in 2035 and 9.06% in 2040.

Other inputs

The remaining inputs have a significantly smaller influence on results. As such, brief description is provided for each.

Other Capex

Other Capex is the capital costs not included under launch or satellite/rectenna build costs. It includes launch insurance, assembly equipment, site grid infrastructure, pre-development costs and the construction of the mission control facility.

Given the value of small-scale SBSP satellites, **launch insurance** is assumed to be required for every launch. Launch insurance typically covers launch plus one year of operation ('launch plus one'). Beyond this, lifetime insurance is rare. It is likely that small-scale SBSP would fully self-insure during operation and would only procure insurance for the launch itself. Within the model, the risk of failure is covered within the Opex calculations under a 'catastrophic failure allowance'.

In 2023, (launch plus one) launch insurance cost rose sharply following two high profile (and high cost) failures.[70] Launch cost premiums using SpaceX's Falcon 9 reached 10% in 2023.[71] It is likely that launch insurance for any early commercial Starship flight would exceed this until its reliability is proven. Additionally, the 'catastrophic failure allowance' does not account for the increased technical risk incurred shortly after launch, including when assembling the satellite. To account for this, a further uplift is applied to launch insurance.

It is assumed that, in 2030, launch insurance will cost 15% of satellite value. Launch insurance is expected to become cheaper throughout the 2030s as Starship's reliability increases and small-scale SBSP moves towards becoming a NOAK product.

Launch insurance is modelled as falling linearly between 2030 and 2040, to 12.5% of satellite value in 2035 and 10% in 2040.

Assembly equipment is required to configure the modules into an operational system in orbit. Each satellite has its own equipment.

The assembly equipment, while simpler than the satellite, will have a higher proportion of heavy metals in its composition. On balance, it is assumed to cost the same amount per

[70] Launch plus 1 satellite insurance - managing the risk of an expensive firework display
[71] Satellite Insurance – An Introductory Guide | Insurance Business America

kilogram as the satellite. As a result, the cost per kilogram is assumed to fall at the same rate as the satellite (including both scale-based and generational improvements).

Additionally, the assembly equipment is assumed to get lighter each year, falling linearly from 10 tonnes in 2030 to 7.5 tonnes in 2040. Assuming cost scales linearly with the mass of required materials, this reduces the total cost of assembly equipment by the same rate.

The cost of the assembly equipment is subject to optimism bias adjustments. The same process is applied as for satellite build costs: the optimistic approach applies no optimism bias; the medium approach applies a 50% optimism bias; and the conservative approach applies a 100% optimism bias.

Using the **optimistic approach**, the progression of assembly equipment cost (for all four satellites) is as follows:

- **2030** - £31.1 million.
- **2035** - £16.2 million.
- **2040** - £8.83 million.

The costs for each year under the **medium** and **conservative** approach are 50% and 100% higher, respectively.

Site grid infrastructure is the cost of the electricity plant and grid connection equipment required at the rectenna. The cost of site grid infrastructure scales with the power output of the constellation. In 2024 prices, the cost is assumed to be £0.15 million per MW. The total cost per constellation is estimated as follows:

- **2030** - £18.6 million.
- **2035** - £25.5 million.
- **2040** - £31.2 million.

Predevelopment costs include research & development, planning, permitting and site preparation. Pre-development costs are assumed to increase slowly as systems get more technologically advanced. Relevant evidence beyond the values provided in Space Solar's financial model (which is based on the 2021 Frazer-Nash report) could not be identified.[4] As a result, Space Solar's estimates are taken forward and pre-development costs per constellation are estimated as follows:

- **2030** - £48.6 million.
- **2035** - £56.9 million.
- **2040** - £62.9 million.

The **control centre capital cost** is the cost of the equipment required to control each constellation. Assumed 2030 control centre capital costs follow that of a facility recently commissioned by ESA at the European Space Operations Centre.[72] The facility is estimated to cost €25.6 million (£21.7 million)[73] and will be delivered in 2030. Importantly, this facility is expected to be able to support multiple critical operations or launches in parallel, so, presumably, a similar facility would be capable of managing more than one constellation at a time. Control centre costs, then are modelled such that half of the facility's cost is attributable to each constellation.

The control centre capital cost is expected to decrease as the number of constellations increases, and as computers and other relevant equipment become cheaper (for a given capability). While this cost reduction is intuitive, it does not easily fit into a learning curve model. Instead, a flat 5% reduction in cost is applied each year. This yields the following costs:

- **2030** - £10.8 million.
- **2035** - £8.36 million.
- **2040** - £6.47 million.

Control centre operating cost

Control centre operating cost is the annual staff and systems cost associated with operating the active constellation(s). Operational costs are composed of the staff and systems required to maintain the rectennas and operate the control centre. It is assumed, via a ROM estimate of likely staff costs, that the operational cost attributable to each constellation is **0.25%** of total Capex each year.

Catastrophic failure allowance

This is a probabilised allowance for the failure of a large number of modules on a satellite due to a catastrophic event (e.g. a collision with space debris). It is based on the cost of replacing the lost capability. The failure allowance is **0.14%** of total Capex each year.

Note that, aside from this allowance, no unavailability analysis is undertaken. It is assumed that there are no losses from outages and maintenance and that catastrophic failures are effectively fixed instantly. In the absence of catastrophic failure 100% availability is assumed.

Summary of input values

Table 27 provides input values for the central baseline scenario.

Node ref	Input node description	2030	2035	2040	Units
[1]	Launch cost per kg	1647	1400	1153	£/kg
[2]	Mass	98500	98500	98500	kg
[4]	Number of satellites	4	4	4	n

72 ESA Signs Contract for Its Satellite Control Centre of the Future - European Spaceflight
73 Using the average 2024 exchange rate 1 GBP = 1.1811 EUR

[5]	Number of rectenna	3	3	3	n
[6]	Satellite build cost, each	103m	61.1m	38.9m	£
[8]	Other Capex	186m	146m	129m	£
[9]	Rectenna size	13.4	13.4	13.4	km^2
[10]	Rectenna cost, per unit area	7.99m	7.20m	6.43m	£/km^2
[12]	Control centre operating cost (% of Capex per year)	0.25%	0.25%	0.25%	n
[13]	Catastrophic failure allowance (% of Capex)	0.14%	0.14%	0.14%	n
[16]	Power to Earth (all four)	124	168	208	MW
[17]	Winter utilisation	57.6%	57.6%	57.6%	n
[18]	Summer utilisation	62.1%	62.1%	62.1%	n
[19]	Hurdle rate	20.0%	13.1%	9.1%	n
[20]	Lifetime	15	15	15	Years

Table 28 provides optimistic baseline input values.

Node ref	Input node description	2030	2035	2040	Units
[1]	Launch cost per kg	1188	1008	827	£/kg
[2]	Mass	98500	98500	98500	kg
[4]	Number of satellites	4	4	4	n
[5]	Number of rectenna	3	3	3	n
[6]	Satellite build cost, each	68.5m	40.7m	25.9m	£
[8]	Other Capex	150m	127m	120m	£
[9]	Rectenna size	13.4	13.4	13.4	km^2
[10]	Rectenna cost, per unit area	7.99m	7.20m	6.43m	£/km^2
[12]	Control centre operating cost (% of Capex per year)	0.25%	0.25%	0.25%	n

[13]	Catastrophic failure allowance (% of Capex)	0.14%	0.14%	0.14%	n
[16]	Power to Earth (all four)	124	168	208	MW
[17]	Winter utilisation	57.6%	57.6%	57.6%	n
[18]	Summer utilisation	62.1%	62.1%	62.1%	n
[19]	Hurdle rate	14.9%	9.8%	6.75%	n
[20]	Lifetime	15	15	15	Years

The results are adjusted to account for solar panel degradation. Solar panel performance is assumed to degrade linearly from 100% output to 90% output throughout the satellite's 15-year lifespan. The impact of this degradation on the LCOE results depends on this hurdle rate: the higher the hurdle rate, the less influence later years (with reduced solar panel output) have on the LCOE results, so the less impact solar panel degradation has on LCOE.

Table 29 presents the adjustment factors applied to the results to account for solar panel degradation.

Baseline	Solar degradation adjustment factor - 2030	Solar degradation adjustment factor - 2035	Solar degradation adjustment factor - 2040
Optimistic	1.034	1.039	1.043
Central	1.029	1.036	1.040
Conservative	1.029	1.036	1.040

Sensitivity analysis

Sensitivity analysis is conducted to explore the robustness of the study's results. Sensitivity is explored in two ways:

- **A Sobol variance analysis** breaks down the variance in the LCOE distribution in terms of the variances of the inputs. It allocates a percentage to each input, which is a measure of the how influential that input is in driving uncertainty in LCOE.
- **A scenario analysis** investigates the impact on LCOE if the key input parameters deviate from the baseline case. Principally, this analysis explores downside risk, including the impact of the improvements forecast from 2030 to 2040 not materialising. Where there is evidence that existing parameters are conservative, upside opportunity is also explored.

Sobol variance analysis

Figure 18 presents the most influential inputs in 2030, as identified in the Sobol analysis.

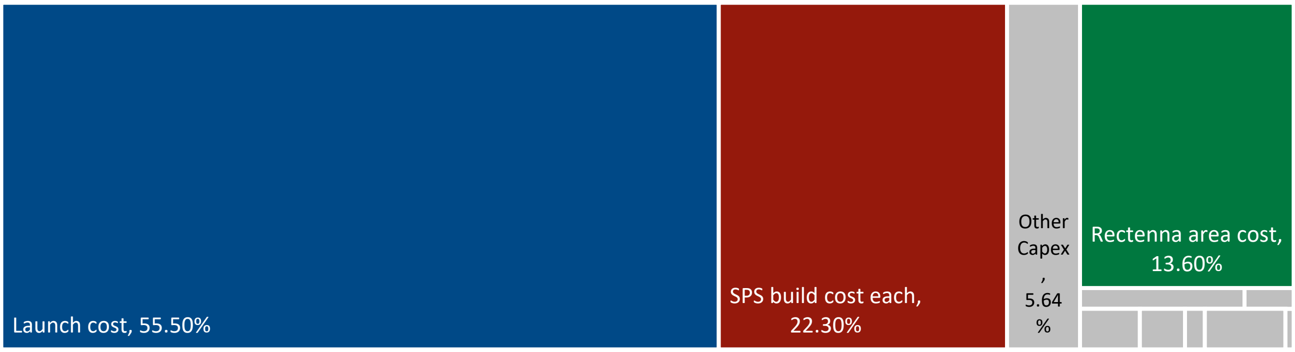


Figure 19 presents the most influential inputs in 2035, as identified in the Sobol analysis.

Figure 20 presents the most influential inputs in 2040, as identified in the Sobol analysis.

Input variations

Table 30 provides an overview of input variations considered for sensitivity analysis.

Input	Variation	Variation description	Impact on LCOE
Launch costs	Ambitious (best case) launch costs	Lower launch costs, in line with some projections that suggest Starship will cost $200/kg to LEO.[74] It is assumed that Starship reaches this capability in 2040. The rate of cost progression from 2030 to 2040 is identical to the baseline scenario.	LCOE decreases
	Launch cost stagnation	Launch cost stagnation – launch costs are as projected in 2030 but then fall at a slower rate than anticipated to 2040. This is modelled as the cost falling half as quickly as baseline.	LCOE increases in 2035 and 2040
	Starship delayed	Starship is delayed until 2035, with an alternative used in 2030. This is modelled as the ‘increased launch costs’ variation for 2030. In 2035, the baseline 2030 cost is used; and in 2040, the baseline 2035 cost is used.	LCOE increases
Satellite build cost and performance	Increased scale benefits (ISB)	Increased scale benefits, using the average aerospace learning factor of 85%.	LCOE decreases in 2035 and 2040
	ISB, 1st gen. modules only	Increased scale benefits of 85% but no improvements (technical or cost) from introducing new generations of module improvements. This represents how a standard aerospace technology might be expected to scale.	LCOE increases in 2035 and 2040
	Module generations (MGs) - slower technical gains	New generation modules achieve a more moderate improvement in W/kg, with £/kg improvement at baseline. This is modelled as half the rate of improvement as baseline.	LCOE increases in 2035 and 2040

[74] The Starship revolution in space | The Strategist

	MGs - slower cost gains	New generation modules achieve a more moderate improvement in £/kg with W/kg improvement at baseline. This is modelled as half the rate of improvement as baseline.	LCOE increases in 2035 and 2040
	MGs - no cost gains	New generation modules achieve no improvement in £/kg with W/kg improvement at baseline.	LCOE increases in 2035 and 2040
	MGs - delay	It takes an additional year for each new generation of modules to be developed. This is modelled as the 2035 and 2040 specification using 2nd and 3rd generation modules, instead of 3rd and 5th generation modules, respectively. The technical and cost improvement associated with each new module is at baseline.	LCOE increases in 2035 and 2040
Rectenna costs	Rectenna costs fall faster	Rectenna costs follow Wright's law with an increased learning rate, distributed uniformly between 75% and 80%	LCOE decreases in 2035 and 2040
	Rectenna costs fall slower	Rectenna costs follow Wright's law with a decreased learning rate, distributed uniformly between 90% and 95%	LCOE increases in 2035 and 2040
Hurdle rate	FOAK hurdle rate 14.9%	A hurdle rate of 14.9% is used for 2030, instead of 20%. Hurdle rates in 2035 and 2040 are adjusted proportionately, assuming progression at the same rate as baseline.	LCOE decreases
	Slower hurdle rate progression	The hurdle rate remains 20% in 2030. However, the rate at which it decreases in 2035 and 2040 is halved compared to baseline	LCOE increases in 2035 and 2040
Lifetime	Uncertain lifetime	Satellite lifetime is modelled as uncertain, uniformly distributed between 12.5 at 17.5 years.	LCOE increases (due to discounting effects)

	Extendable lifetime	Satellite lifetime is modelled as extendable, using a uniform distribution between 15 and 17.5 years.	LCOE decreases
	Shorter lifetime	Satellite lifetime is modelled as lower than expected, using a uniform distribution between 12.5 and 15 years.	LCOE increases

Input variation results

Figure 21 presents the results of the individual input variation analysis for a constellation launched in 2030.

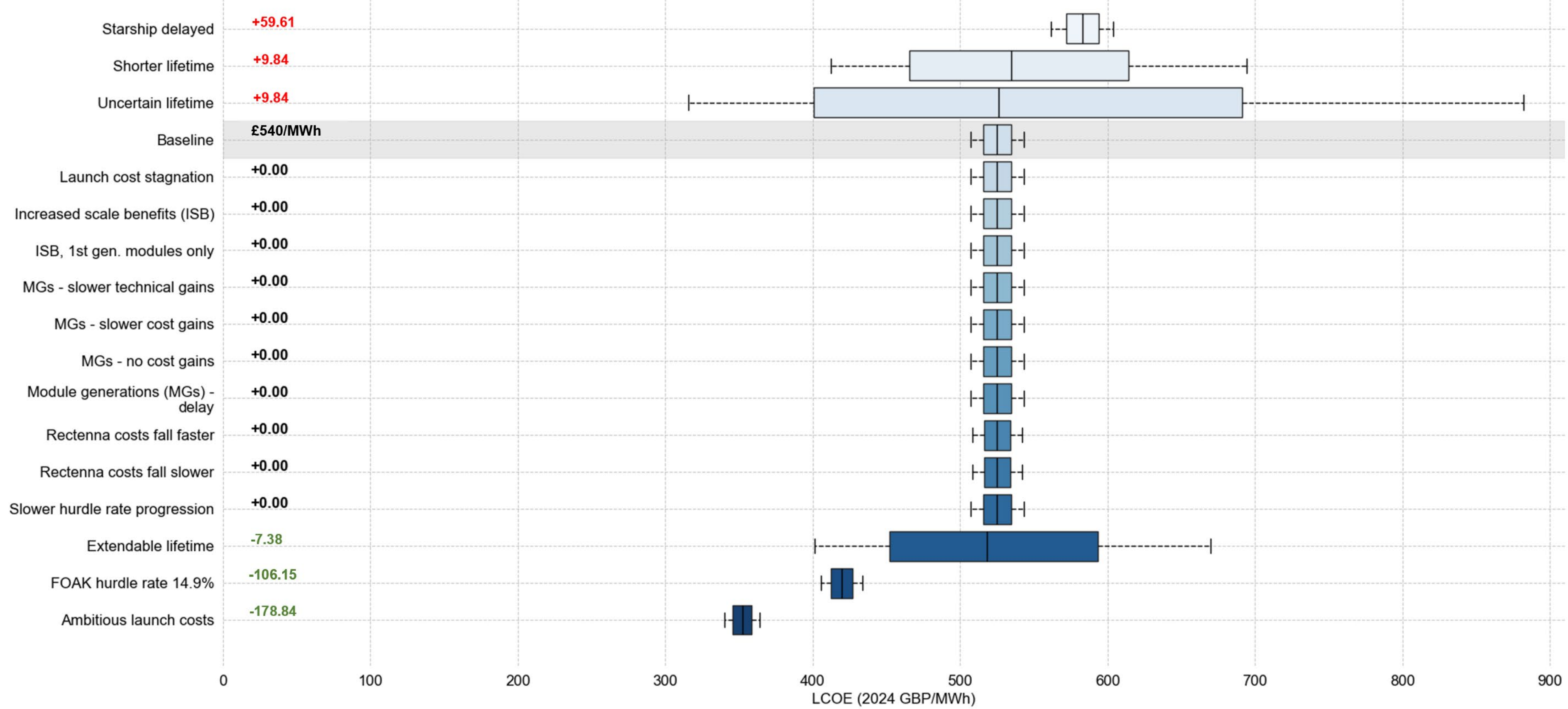


Figure 22 presents the results of the individual input variation analysis for a constellation launched in 2035.

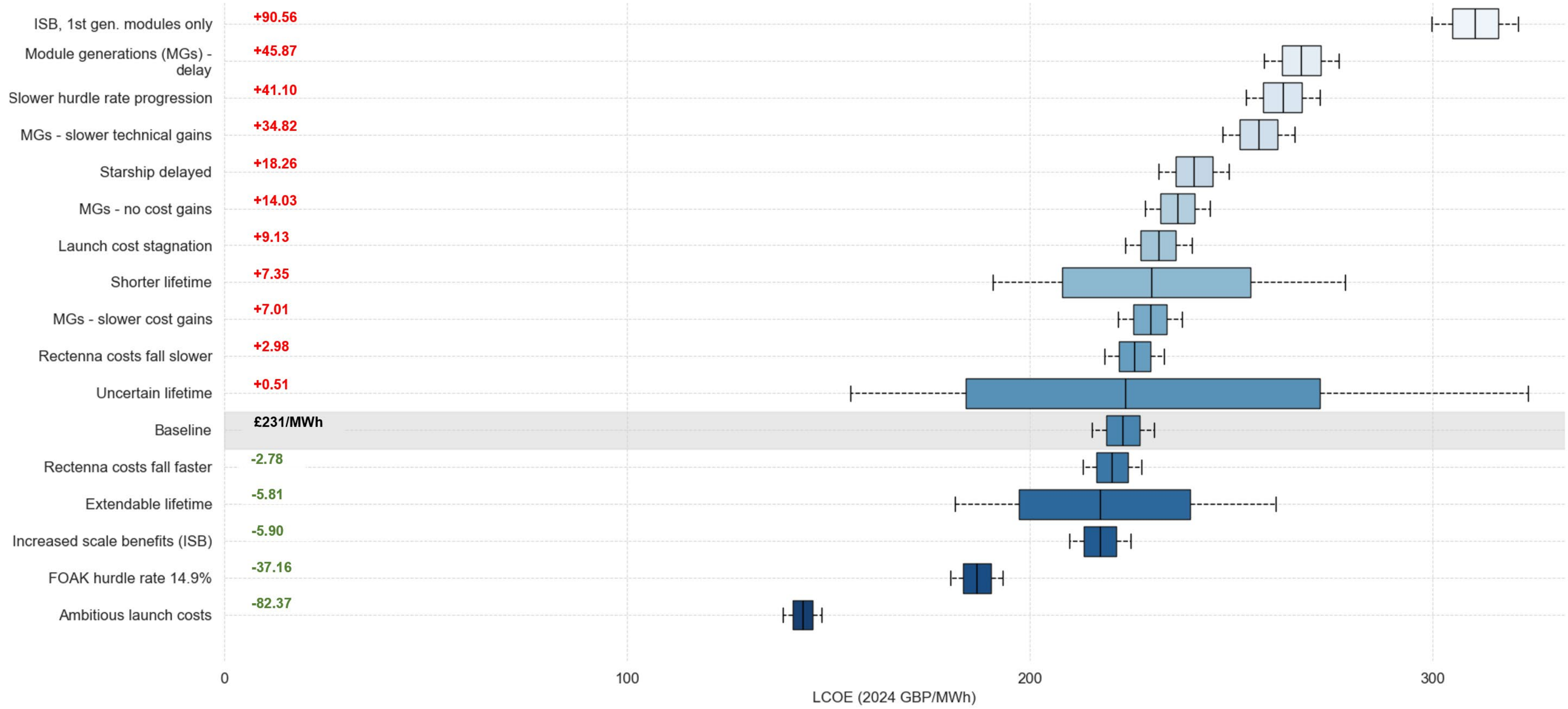
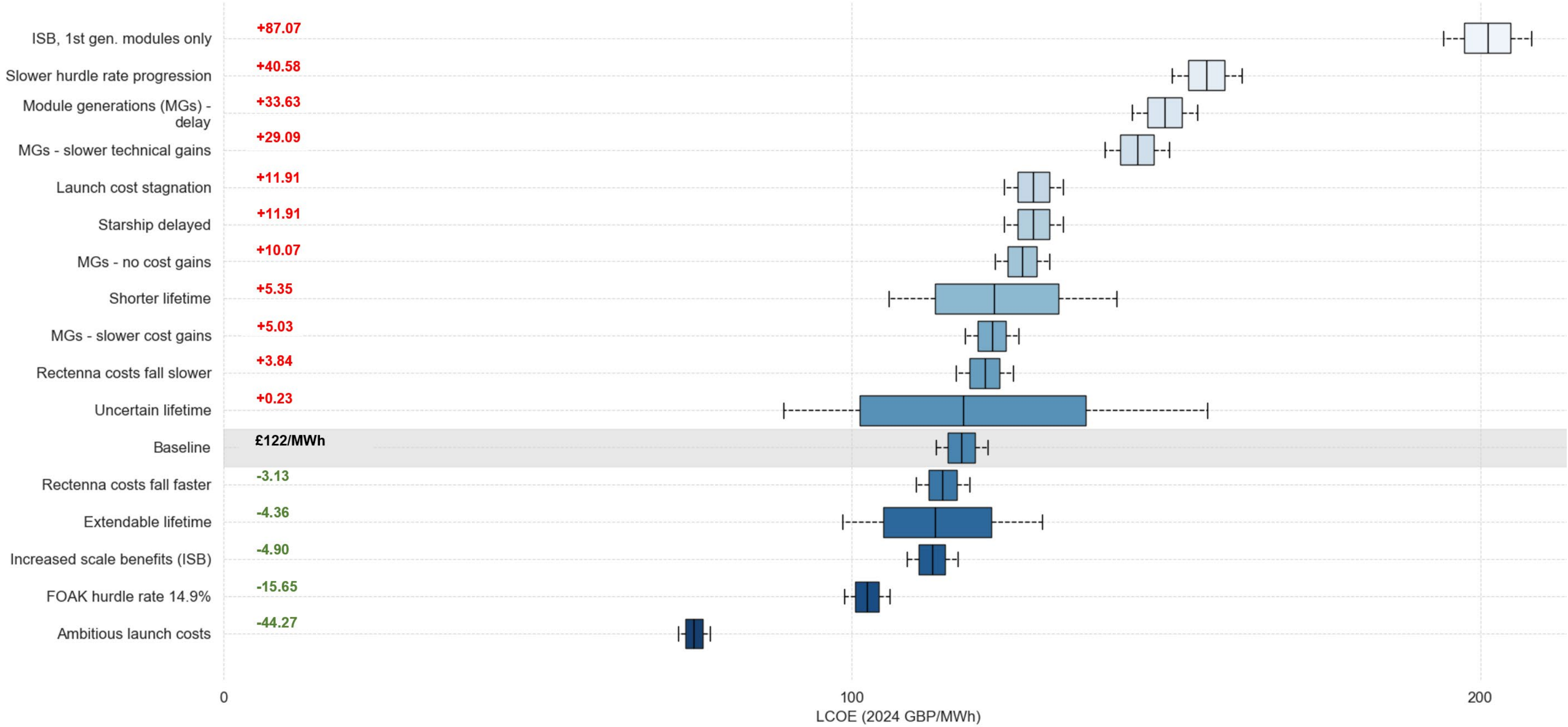


Figure 23 presents the results of the individual input variation analysis for a constellation launched in 2040.



9. Annex B: GB Ancillary Markets

Table 31 summarises the existing and emerging GB ancillary services markets, including the requisite technical capability, procurement timescales, expected/existing market sizes and an evaluation of the suitability of small-scale SBSP to provide the service.

Service	Technical capability	Requirements and procurement	Market size and expenditure	Evaluation
Short term operating reserve (STOR)	In scenarios where network demand is greater this service is used to obtain reserves of power to meet the network requirements. The required response and sustain times for this service are 20 minutes and 2 hours, respectively.	Being phased out		
Balancing Reserve	Secures headroom and foot-room for regulating reserve 1 MW minimum entry requirement 30-minute Service Window (10-minute ramp)	Procured day ahead Split into negative and positive products Supplier must be a BM unit	Expected service requirement for 500 to 2,500 MW	Provision of negative reserve possible though a battery would potentially be required to ensure it meets the 30-minute service window requirement.
Quick Reserve	Pre-fault disturbances 1 MW minimum entry requirement	Procured day ahead	Expected service requirement for 300 to 1,400 MW	Provision of negative reserve possible though a battery would potentially be required to

	Activation 5 to 15 minutes (1 minute ramp). 30-minute service window.	Split into negative and positive products Availability and utilisation payments		ensure it meets the 30-minute service window requirement.
Slow Reserve	Post-fault to recover system frequency from large loss 1 MW minimum entry requirement. Must be able to deliver for a full 2-hour service window.	Procured day ahead Split into negative and positive products Availability and utilisation payments	Expect service requirement of 1,400 MW	Provision of negative reserve possible though battery would likely be required to ensure it meets to 2-hour continuous delivery requirement
Dynamic Regulation	Pre-fault service to keep frequency close to statutory limits 2s response time	High and low frequency response procured separately on the Enduring Auction Capability. EFA block procurement.	Up to 300 MW	Would likely require a co-located storage asset to provide the headroom and footroom flexibility and to comply with EFA block service window.
Dynamic Moderation	Pre-fault service to mitigate more volatile frequency deviations 0.5s response time	High and low frequency response procured separately on the Enduring Auction Capability. EFA block procurement.	Up to 300 MW	Would likely require a co-located storage asset to provide the headroom and footroom flexibility and to comply with EFA block service window.

Dynamic Containment	Post-fault service to bring back frequency back into statutory limits. 0.5s response time	High and low frequency response procured separately on the Enduring Auction Capability. EFA block procurement.	Up to 1,400 MW	Would likely require a co-located storage asset to provide the headroom and foot-room flexibility and to comply with EFA block service window.
Obligatory Reactive Power Service	Generators must be able to operate between 0.85 lagging and 0.95 leading power factor.	Designed for generators and baked into a connection agreement.	£190m 31,000 GVArh	Required to participate. Will require onshore assets such as a converter station.
Voltage Network Services Procurement	Technical requirements are specific to each tender.	Locational requirement identified and a tender process for long term contracts initiated.		Reactive power requirement potentially too large and location specific.
Reactive Power Services	Technical requirements not yet confirmed.	Long term market (Y-4) and mid-term market (Y-1) are most likely.		Potentially able to participate once the markets have been implemented and requirements defined
Energy System Restoration	Transmission-connected anchor Transmission-connected top-up Anchor generators (distribution)	Previously bilateral contracts Will go to tender in the future	£66m	Should be able to provided that it can energise its connection

	Top-up services (distribution)			

10. Annex C: Global market analysis

This analysis assesses 10 markets, with a summary of the TAM, SAM and SOM provided together with the basis of estimate.

The benefits and capabilities of space-based solar power are highly relevant to these markets. The markets presented could benefit substantially from SBSP's ability to:

- Provide continuous firm all-weather power, giving reliability of energy.
- Wirelessly dispatch power to remote locations overcoming logistic costs and difficulties.
- Provide resilience in combination with other energy sources.

The rectenna siting is flexible, with options for coastal as well as land sites, and offering low visual impact. The ground-based operating cost is low as rectennas are low in complexity with no moving parts, thus requiring many fewer expert technicians compared to small modular reactors.

Customers within several of these markets have engaged strongly with Space Solar, underlining the potential of SBSP to provide competitive electricity off the grid. In all cases, the proportion of addressable market that is obtainable is highly unclear, so it is assumed that SOM is 50% of SAM for every market.

Mining

Total energy consumption of the mining sector was 3,333 TWh per annum in 2023.[75] Mining demand is set to grow quickly, with a significant demand provided by the growing need for critical minerals in technologies such as wind, solar and batteries. Total demand for 'transition minerals' would require mining to increase by between 1,000% - 7,000%, although this is clearly not practical. It is instead assumed that mining activity will increase by 50% over the next 25 years, and energy consumption will increase proportionally.[76] So TAM is calculated as:

$$3{,}333 \text{ TWh} \times 1.5 = 5{,}000 \text{ TWh per year}$$

The proportion of TAM that is SAM is defined by:

- The proportion of mines that can site a rectenna nearby.
- The proportion of the mines' energy demand that SBSP can service

Mines are typically sited in remote areas, so a reasonable assumption is that for a substantial percentage (assume 30%) it will be possible to site a rectenna nearby.

[75] CEED The Future: "Published information indicates that the entire mining industry consumes approximately 12 EJ per year." 1 EJ = 277.8 TWh.

[76] Mark Mills, energy expert and senior fellow, Manhattan Institute. 2023 lecture. https://www.youtube.com/watch?v=sgOEGKDVvsg

Assuming that 40% of total energy demand would be provided by SBSP for these mines, SAM is calculated as:

$$5{,}000 \times 0.3 \times 0.4 = 600 \text{ TWh per year}$$

SOM is:

$$600 \times 0.5 = 300 \text{ TWh per year}$$

Water desalination

According to the International Desalination Association in 2022, there were 22,800 desalination plants worldwide, generating around 110 million cubic meters of fresh water daily,[77] many in the Middle East and North Africa. Modern seawater reverse osmosis (SWRO) plants are energy efficient, consuming around 3kWh per cubic meter of water produced. Thus total energy demand, TAM, is calculated as

$$110{,}000 \times 0.003 \text{ MWh} = 330 \text{ GWh per day} = 120.5 \text{ TWh per year}$$

This TAM is conservative because it does not account for future growth in water desalination. There has been a fivefold increase in water desalination production over the last 20 years;[78] if this trend were to continue, then TAM would be significantly larger.

By definition, water desalination occurs in coastal areas, and so there is likely to be a high percentage of sites which could host an offshore rectenna, assumed at 75%. Assuming 40% could be powered by SBSP, SAM is calculated as:

$$120.5 \text{ TWh per year } \times 0.75 \times 0.4 = 36 \text{ TWh per year}$$

And SOM is:

$$36 \text{ TWh per year} \times 0.5 = 18 \text{ TWh per year}$$

Small island nations

As of June 2023, the United Nations recognizes 57 Small Island Developing States (SIDS) with a combined population of approximately 73.5 million people. These nations are distributed across three regions:

- Caribbean: 29 countries and territories.
- Pacific: 20 countries and territories.

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[77] International Desalination and Reuse Association (IDRA) https://idadesal.org/about/
[78] Le Monde report https://www.lemonde.fr/en/environment/article/2023/06/16/seawater-desalination-booms-despite-environmental-cost_6032699_114.html

- Atlantic, Indian Ocean, and South China Sea (AIS): 8 countries and territories.

It is important to note that while SIDS are often small in land area, they vary significantly in population size. For example, the Dominican Republic and Haiti, located in the Caribbean, each have populations exceeding 10 million, collectively accounting for around 60% of the SIDS population.

In contrast, other SIDS have much smaller populations. For instance, the Cook Islands, a self-governing territory in free association with New Zealand, has a population of about 15,000 people.

According to the World Bank, in 2014, the average electricity consumption for middle-income countries was approximately 1,878 kWh per person.[79] This value is assumed to grow over time as SIDS develop. Assuming 3,000 kWh per person per year, TAM is calculated as:

$$3{,}000\ \text{KWh} * 73{,}500{,}000 = 220{,}500\ \text{TWh per year}$$

Given the proximity to water, it is likely that most locations (assumed 70%) would be able to site an offshore rectenna nearby. Given low levels of electrification in developing countries, it is unlikely that SBSP could provide a large portion of total power. If SBSP could provide 1% of the required power, then SAM is given by:

$$220{,}500\ \text{TWh per year} \times 0.7 \times 0.01 = 1{,}544\ \text{TWh per year}$$

SOM is:

$$1{,}544\ \text{TWh} \times 0.5 = 772\ \text{TWh per year}$$

Iron and steel production

As of 2023, the global crude steel production capacity is estimated at approximately 2,432 million metric tons (MMT). China accounts for about 54% of global steel production, and Russia contributes approximately 4.6%. Excluding these two countries, the remaining global steel production capacity is around 1,100 MMT.[80]

Energy consumption depends on the process used:

- Blast Furnace–Basic Oxygen Furnace (BF-BOF) Route: 20 to 35 gigajoules (GJ) per metric ton of crude steel produced.
- Electric Arc Furnace (EAF) Route: 2.25 GJ per metric ton of steel produced, which is about 10 times less energy than the BF-BOF route.

[7979] https://data.worldbank.org/
[80] https://en.wikipedia.org/wiki/List_of_countries_by_steel_production

- Direct Reduced Iron–Electric Arc Furnace (DRI-EAF) Route: Approx 12.5 GJ per metric ton of steel produced.

Assuming an average of 10 GJ per metric ton, this is 0.00278 GWh. TAS is calculated as:

$$1{,}100\ \mathrm{MMT} \times 10\,\frac{\mathrm{GJ}}{\mathrm{MT}} \times 0.000278\,\frac{\mathrm{GWh}}{\mathrm{GJ}} = 3{,}055{,}600\ \mathrm{GWh\ per\ year}$$

Most production facilities are in coastal areas, so should often be possible to site a rectenna nearby. It is assumed that this is possible 50% of the time. It is assumed that SBSP would meet 40% of the facilities' energy demand. SAM is calculated as:

$$3{,}055{,}600\ \mathrm{GWh\ per\ year} \times 0.5 \times 0.4 = 611\ \mathrm{TWh\ per\ year}$$

SOM is:

$$611\ \mathrm{TWh\ per\ year} \times 0.5 = 306\ \mathrm{TWh\ per\ year}$$

Data centres

As of 2022, data centres worldwide consume between 240 to 340 terawatt-hours (TWh) of electricity, accounting for approximately 1% to 1.3% of global electricity demand.[81] As AI and cloud computing accelerates, this energy demand is expected to grow very substantially. Microsoft is re-commissioning a nuclear power station at 3 Mile Island to power a single data centre. The International Energy Agency (IEA) anticipates that data centre electricity consumption will more than double from 415 TWh in 2024 to 945 TWh in 2030. So TAM is assumed to be 945 TWh per year.

A review of data centre locations suggests that the majority are located in the middle cities.[82] Therefore, it is assumed that only 15% of locations will be suitable for siting a rectenna nearby. We assume that up to 40% of data centre energy demand could be provided by SBSP, so SAM is calculated as:

$$945\ \mathrm{TWh\ per\ year} \times 0.15 \times 0.4 = 57\ \mathrm{TWh\ per\ year}$$

And SOM is:

$$57\ \mathrm{TWh\ per\ year} \times 0.5 = 28\ \mathrm{TWh\ per\ year}$$

Cold ironing for merchant shipping

Cold ironing is the term for providing shore power to merchant shipping to avoid them burning diesel while berthed, including container ships and cruise liners. This reduces local pollution

[81] Energy and AI
[82] datacentremap.com

and carbon footprint of shipping. There are estimated to be 405 major container ports globally, and there are around 1,200 ports worldwide that handle cruise liners. It is assumed that the target market is 1,200 ports. In a 2023 study, the total energy demand for ships hotelling at the PSA terminal in Genoa was approximately 20,231 MWh annually.[83] As such, TAM is calculated as:

$$20 \text{ GWh per year} \times 1{,}200 = 24 \text{ TWh per year}$$

Given the location of the ports, it is assumed that the majority (70%) of ports can locate a rectenna offshore. It is also assumed that 40% of the energy demand will be met by SBSP. SAM is given by:

$$24 \text{ TWh per year} \times 0.7 \times 0.4 = 6.72 \text{ TWh per year}$$

SOM is:

$$6.72 \text{ TWh per year} \times 0.5 = 3.36 \text{ TWh per year}$$

Dual use power with terrestrial solar

Terrestrial solar farms in dry countries have a utilisation of around 20%. SBSP, with a rectenna co-located over the solar farm, could top up the remaining 80% when the sun isn't shining at that point on Earth. Tests would be needed to establish that the minimal shadowing from the rectenna elements is acceptable to the solar farm performance. There are more than 7,650 major solar projects (over 100 MW) currently in the Solar Energy Industries Association database,[84] representing over 299 GW of capacity.

Assuming 10% of these projects are the right size and shape to integrate a rectenna, and the systems provide 150 MW of SBSP capacity, the TAM is calculated as:

$$7{,}650 \times 0.1 \times 0.15 \text{ GW} \times 8760 \frac{\text{hours}}{\text{year}} = 1{,}005 \text{ TWh per year}$$

For economic and operational reasons, it is likely only a minority (20%) of sites would host a rectenna. As such, SAM is:

$$1{,}005 \text{ TWh per year} \times 0.2 = 201 \text{ TWh per year}$$

And SOM is estimated as:

$$201 \text{ TWh per year} \times 0.5 = 100 \text{ TWh per year}$$

[83] https://www.mdpi.com/2305-6290/7/2/28
[84] https://seia.org/research-resources/major-solar-projects-list

Green hydrogen production

The International Energy Agency (IEA) reports that if all announced low-emission hydrogen projects are realised, annual production could reach 38 million tonnes by 2030.[85] Notably, 17 million tonnes of this projection come from projects at early stages of development. However, BloombergNEF (BNEF) anticipates that only about 30% of the 1,600 announced low-carbon hydrogen projects will materialise by 2030, resulting in an estimated 16.4 million metric tons per year of clean hydrogen supply.[86]

Producing 1 kg of green hydrogen via electrolysis requires approximately 55 kilowatt-hours (kWh) of electricity.[87] As a result, TAS is:

$$55\,\frac{\text{kWh}}{\text{kg}} \times 16{,}400{,}000{,}000\ \text{kg} = 902\ \text{TWh per year}$$

Given the requirement for water, a large proportion of plants are expected to be at sea, enabling the majority (assumed 80%) to be able to site an offshore rectenna nearby. If 60% of energy demand is provided by SBSP, then SAM is calculated as:

$$902\ \text{TWh per year} \times 0.8 \times 0.4 = 433\ \text{TWh per year}$$

And SOM is:

$$433\ \text{TWh per year} \times 0.5 = 216\ \text{TWh per year}$$

Deployed operating bases

There are several hundred deployed military bases globally across NATO members.

In 2020, U.S. military installations in Europe consumed 2.64 TWh of energy. This consumption encompasses electricity, natural gas, oil, and coal.[88] This is the assumed value taken forward for TAM.

It is unclear what proportion of these military basis would be able to site a rectenna; a value of 50% is assumed. It is assumed that 30% of the bases’ energy demand can be satisfied by SBSP on average. So SAM is calculated as:

$$2.64\ \text{TWh per year} \times 0.5 \times 0.3 = 396\ \text{GWh per year}$$

SOM is given by:

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[85] https://www.iea.org/reports/global-hydrogen-review-2023/executive-summary
[86] https://about.bnef.com/blog/hydrogen-supply-outlook-2024-a-reality-check
[87] https://en.wikipedia.org/wiki/Hydrogen_production
[88] https://climate.watson.brown.edu/news/2022-04-28/mapping-us-military-dependence-russian-fossil-fuels

$$396 \text{ GWh per year} \times 0.5 = 198 \text{ GWh per year}$$

Polar research stations

Polar research stations provide a significant source of demand that is serviceable by small-scale SBSP. Engagement with the British Antarctic Survey (BAS) has revealed that energy consumption at research stations is highly constrained, and stations often use on-site diesel generation, which typically costs £3,000/MWh.[89] The viability of renewable technologies is significantly curtailed by the frequent harsh weather and intermittency, making it difficult for BAS to reduce this energy cost.

A set of four MVP satellites in a polar LEO would provide 31 MW at around 25% utilisation to target sites in the Antarctic. Small-scale SBSP is likely to significantly undercut current on-site diesel generation from the first installation, proving cheaper and cleaner power. This implies demand for small-scale SBSP in this market could materialise as early as 2030.

There are 70 permanent polar research bases across Antarctica and up to a further 40 more seasonal bases in the Arctic. According to NREL, for the full year of 2002, the electrical consumption for McMurdo was 15,823 MWh, but very constrained by the cost and logistical challenges. According to NREL the cost of energy supplied by diesel generators is typically £3,000/MWh.[90]

Assuming that the average consumption per station is half the value of McMurdo (similar to the average across the British stations), then TAM is given by:

$$70 \text{ stations} \times 8 \text{ GWh per year} = 560 \text{ GWh per year}$$

It is assumed that, due to the remote location, around 75% of locations could site a rectenna nearby. If 30% of the research stations' energy can be provided by SBSP, then SAM is:

$$560 \text{ GWh per year} \times 0.75 \times 0.3 = 126 \text{ GWh per year}$$

And SOM is:

$$126 \text{ GWh per year} \times 0.5 = 63 \text{ GWh per year}$$

[89] https://www.nrel.gov/news/features/2024/how-to-power-south-pole-with-renewable-energy-technologies.html
[90] https://www.nrel.gov/news/features/2024/how-to-power-south-pole-with-renewable-energy-technologies.html

11. Annex D: Energy systems benefits estimation methodology

The Integrated Whole Energy Systems (IWES) model is used to quantify the system impacts of SBSP across various scenarios. A system without SBSP is used as the counterfactual scenario. The effects of SBSP on the system costs and changes in the optimal energy infrastructure portfolio and operational decisions are compared and evaluated against the counterfactual. The system background used in this study is the GB 2035 scenario, based on the energy demand postulated by the FES Electric Engagement scenario for 2035.

IWES is a least-cost optimisation model that minimises long-term investment and short-term operating costs across multi-energy systems (electricity, heating, hydrogen) from the supply side, and energy network to the end-customers while meeting the required carbon targets and system security constraints. IWES also optimises the deployment of flexibility technologies such as thermal energy storage (TES), electricity storage such as Pumped Hydro Energy Storage (PHES) and Battery Energy Storage System (BESS), hydrogen storage, demand response technologies (e.g. smart electric vehicle charging system with and without vehicle-to-grid capability, industrial and commercial sector demand response), interconnection with Europe, electrolysers, and generation flexibility to ensure adequate generation capacity during peak demand with low renewable output. The model encompasses the energy system, ranging from the local district level to the national level, and the interactions between Great Britain (GB) and the European energy systems. IWES also considers the system's operational requirements, such as frequency response and reserves (which has a timeframe of milliseconds to minutes), dispatch problems (hours, days or seasons), and long-term investment problems (years) simultaneously.

IWES has been used in numerous research studies to examine the impact of emerging technologies on the future GB energy system. A list of selected studies that used IWES is provided below.

1. D. Pudjianto, C. Frost, D. Coles, A. Angeloudis, G. Smart, and G. Strbac, "UK studies on the wider energy system benefits of tidal stream," Energy Adv., 2023, doi: 10.1039/d2ya00251e.[91]

2. D. Pudjianto and G. Strbac, "Whole system value of long-duration electricity storage in systems with high penetration of renewables," *iEnergy*, vol. 1, no. 1, pp. 114–123, Mar. 2022, doi: 10.23919/IEN.2022.0004.[92]

[91] UK studies on the wider energy system benefits of tidal stream - Energy Advances (RSC Publishing)
[92] Whole system value of long-duration electricity storage in systems with high penetration of renewables | TUP Journals & Magazine | IEEE Xplore

3. G.Strbac, D. Pudjianto, et al,"Whole Systems Energy Modelling for Heat Transformation", a report to the Department for Business, Energy, and Industrial Strategy UK, January 2021.[93]

4. D.Pudjianto, H.Ameli, G.Strbac, "The Role and Value of Hydrogen in Future Zero-Carbon Great Britain's Energy System", a report to Cadent, October 2023.[94]

5. Carbon Trust, G.Strbac, D.Pudjianto,"Flexibility in Great Britain," May 2021.[95]

The energy system modelling is provided by I C Consultants Limited which is the wholly owned consultancy company of Imperial College London. Due to its governance and as a matter of university policy, I C Consultants cannot warrant that the deliverable doesn't infringe third party intellectual property rights (IPR). I C Consultants has not provided a licence to their background IPR. But this is a non-issue as I C Consultants has provided a warranty that no licence to their background IPR shall be required to utilise any foreground IPR which includes the energy system modelling.

[93] https://www.imperial.ac.uk/media/imperial-college/energy-futures-lab/research/Whole-Energy-System-Modelling-for-heat-decarbonisation_ICL_2021[2].pdf
[94] https://cadentgas.com/nggdwsdev/media/media/The-Role-of-Hydrogen-Imperial-College-London.pdf
[95] https://publications.carbontrust.com/flex-gb/analysis/

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