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

Executive Summary

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Executive Summary

Study Aims

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

The study aimed to provide a holistic assessment of the required investments, associated costs and risks and expected strategic, environmental, economic and societal benefits of adding this space-based energy source to the European energy mix to meet Net Zero carbon by 2050.

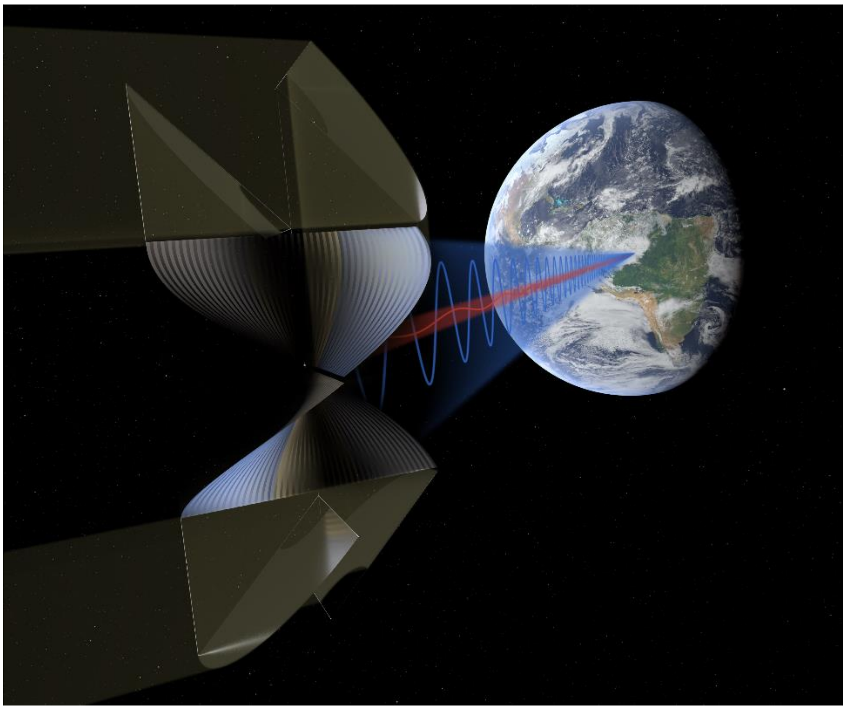
Context

The technical and societal challenges of Net Zero are recognised, and new energy technologies are being explored. The need for base load energy is important to help ensure grid stability with a high percentage of intermittent renewable technologies in the energy mix. SBSP is a developing technology with the potential to generate base load energy, and it has not to date been considered by European governments.

SBSP is the concept of collecting solar energy in space using very large satellites, typically in a Geostationary Earth Orbit (GEO), converting the electricity to microwaves and beaming it to a fixed point on Earth via wireless power transmission (WPT).

There are several SBSP concepts worldwide, but not all offer the capability to deliver baseload continuous power. CASSIOPeiA—a SBSP satellite designed by the British company International Electric Company (IECL)— is one of the three most developed concepts with the most data, and its architecture is assumed as the reference design for this study (Figure 1).

Figure 1 CASSIOPeiA Solar Power Satellite Concept – the reference design for this study. Rendering of CASSIOPeiA in space with superimposed pilot beam and microwave power transmission

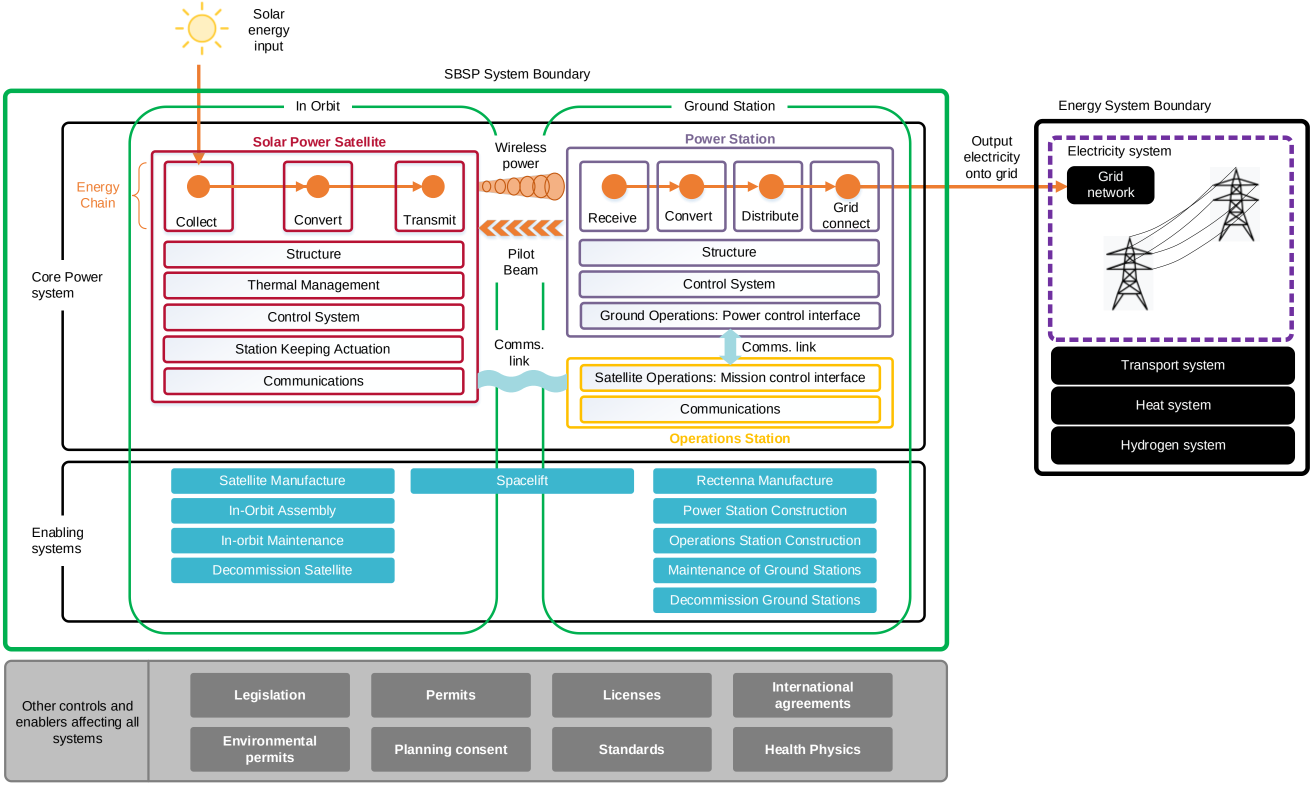


Key Findings

Technical Feasibility

The technical feasibility assessment was based on the system breakdown shown in Figure 2. It comprised an evaluation of the technology maturity and development degree of difficulty, to highlight the challenges of introducing an operational system by 2040, at the latest.

Figure 2 SBSP - System Breakdown



The outcome of the assessment is documented in Table 1. The assessment concluded that there are a small number of critical system elements that need substantial research and development, to overcome technical challenges so they can be progressed through the technology readiness levels. The most significant challenges include:

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

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

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

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

There are several other non-technical challenges that will need to be addressed to realise a European SBSP system. They include (but are not limited to) the safety of the equipment (including microwave beam), public acceptance, regulatory / legal standards, security, and environmental impacts.

Table 1 Technical Feasibility Assessment – Summary of Technology Readiness Levels and Development Degree of Difficulty

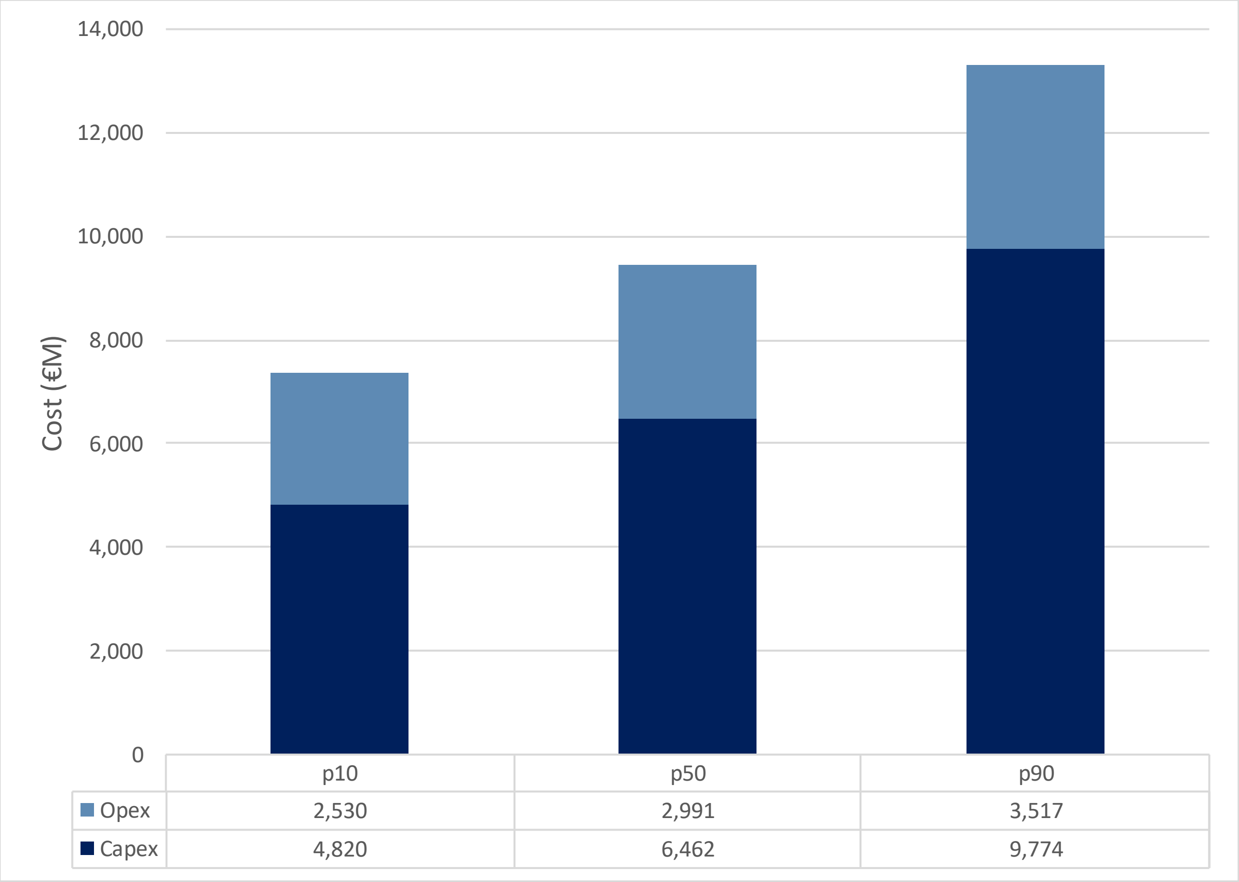
Subsystem element	TRL	Development Degree of Difficulty
Core Power Systems		
Satellite		
Satellite collect	5	High
Satellite convert	2	Medium
Satellite transmit	4	Very High
Satellite structure	3	Very High
Satellite thermal management	3	High
Satellite control system	4	Medium
Satellite station keeping	3	High
Satellite communications	6	Low
Ground Station		
Ground receive	4	High
Ground convert	7	Low
Ground distribute	7	Low
Ground grid connection	8	Very Low
Ground structure	7	Low
Ground control system	6	Medium
Ground operations: Power Control Interface	8	Low
Satellite operation: Mission Control Interface	4	High
Ground communications	4	Medium
Enabling Systems		
Satellite		
Spacelift	7	High
Satellite manufacture (ground)	6	Low

Subsystem element	TRL	Development Degree of Difficulty
In-orbit assembly	3	Very High
In-orbit maintenance	3	Very High
Decommission satellite	2	Very High
Ground Stations		
Rectenna manufacture	4	Medium
Power station construction	8	Very Low
Operation station construction	8	Very Low
Maintenance of ground stations	7	Very Low
Decommission ground stations	8	Very Low

System Costs

The analysis derived operational expenditure (Opex) and capital expenditure (Capex) estimates and calculated a levelised cost of electricity (LCOE) value using these estimates and an industry standard formula. It estimates Capex costs for a first of a kind (FOAK) SBSP system in current year (2022) prices between €4.8bn (p10) and €9.8bn (p90) using a European-wide average for the satellite elevation angle and land prices, and a 20% hurdle rate (Figure 3)[1]. Using the same assumptions Opex over a 30-year life is estimated to lie be between €2.5bn (p10) and €3.5bn (p90). This results in a total FOAK SBSP system cost for Europe between €7.3bn (p10) and €13.3bn (p90) in 2022 prices.

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



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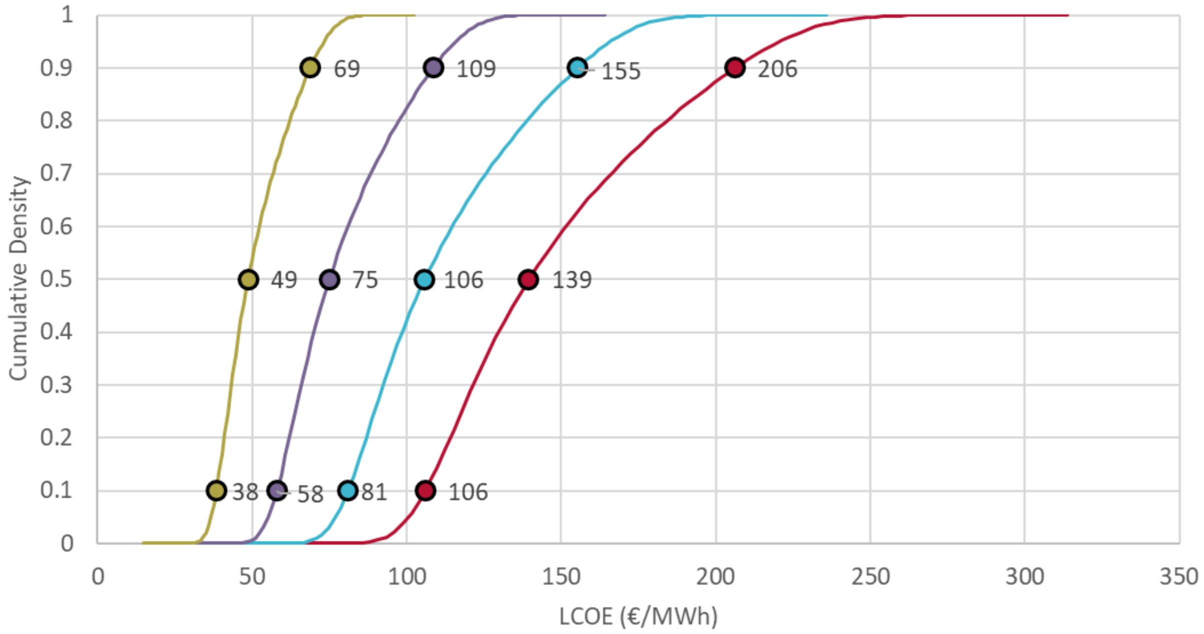
[1] The cost model is probabilistic so treats all input parameters as ranges. It therefore produces probability functions. The p10, p50 and p90 values refer to the 10th, 50th and 90th percentile of the distribution function respectively.

As a result of learning curves and economies of scale the cost of subsequent systems is expected to be lower. Cost estimates for the tenth of a kind system were calculated. These costs were used to infer the likely future whole system costs for a scaled European wide solution to meet Net Zero energy generation targets.

The Capex costs for the tenth of a kind (10OAK) system are estimated to range between €2.5bn (p10) and €3.5bn (p90), using a 20% hurdle rate. Assuming a build rate of two satellites per year, this price could be achieved by 2045 (or sooner with an accelerated development timeline – see below).

LCOE estimates for the FOAK (20% hurdle rate) suggest a range between €106/MWh (p10) and €206/MWh (p90). As the development programme progresses, and the delivery risks reduce, investors who finance the construction and operation of the system may accept a lower risk adjusted cost of capital. A sensitivity analysis on the hurdle rate suggests an LCOE for the FOAK as low as €38/MWh (p10) and €69/MWh (p90) with a 5% hurdle rate.



The tenth system is likely to benefit from less delivery risk than the first, and so a lower hurdle rate might be more appropriate. A sensitivity analysis of the impact of the hurdle rate on the tenth system suggests the LCOE could be as low as €49/MWh (p90). Further sensitivity analysis demonstrates that spacelift costs significantly affect the LCOE — predominantly because they account for a large proportion of total system costs. Conversely, the LCOE is relatively insensitive to changes in the structural mass ratio. While mass of the overall system is a key factor that influences the overall system cost, the change in overall mass that needs to be put into orbit is relatively small.

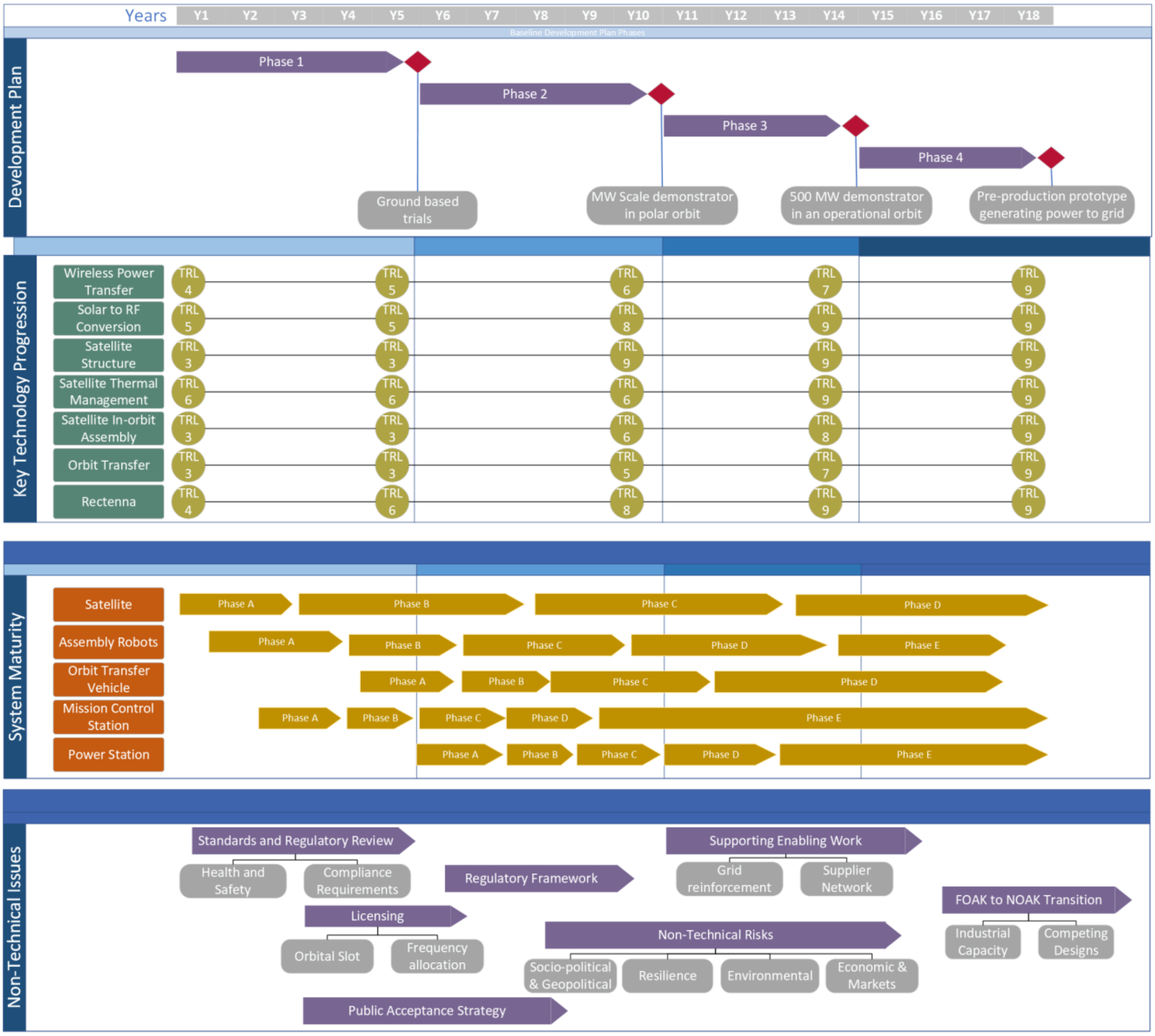
Table 2 SBSP LCOE and VALCOE: Indicative Values as a function of choice of hurdle rate

Hurdle rate	FOAK or 10-OAK	LCOE, P90	Comparison to base case
20%	**FOAK**	**206.3**	n/a
20%	**10-OAK**	**155.5**	n/a
15%	FOAK	155.2	~25% more competitive
15%	10-OAK	116.0	~25% more competitive
10%	FOAK	108.6	~45% more competitive
10%	10-OAK	79.9	~50% more competitive
5%	FOAK	68.8	~65% more competitive
5%	10-OAK	49.1	~65% more competitive

Development Programme & Costs

Figure 4 presents a four-stage development programme structured in a sequence designed to mature the technologies needed for the SBSP system, through a series of increasingly large and complex prototypes to develop the design of the system, leading to a full-scale pre-production operational prototype.

Figure 4 Outline Development Plan



Costs for each phase of the development programme were estimated by adopting a hybrid approach of benchmarking and detailed bottom-up costing. They suggest a timeline of 18 years to a fully operational prototype would cost between €8bn and 16bn. An accelerated timeline suggests the development phase could conclude 4 years earlier, with sufficient investment.

A SBSP solution for Europe would comprise high up-front capital costs and a significant development programme which carries technical delivery risk, followed by back-ended financial payback. To finance such a programme would need significant public sector intervention to bridge the technical valley of death, and provide commercial investors with enough confidence in the viability of the system for it to become commercilased. The study estimates public funding between 30% and 58% for the R&D phases as optimal to overcome the perceived technical risks of the development programme.

Table 3 Development Cost Estimates

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

Cost and Benefit Analysis

The net benefits estimated in this study amount to **€183bn**, as detailed in Table 4

Table 4 NPV of SBSP benefits: Summary

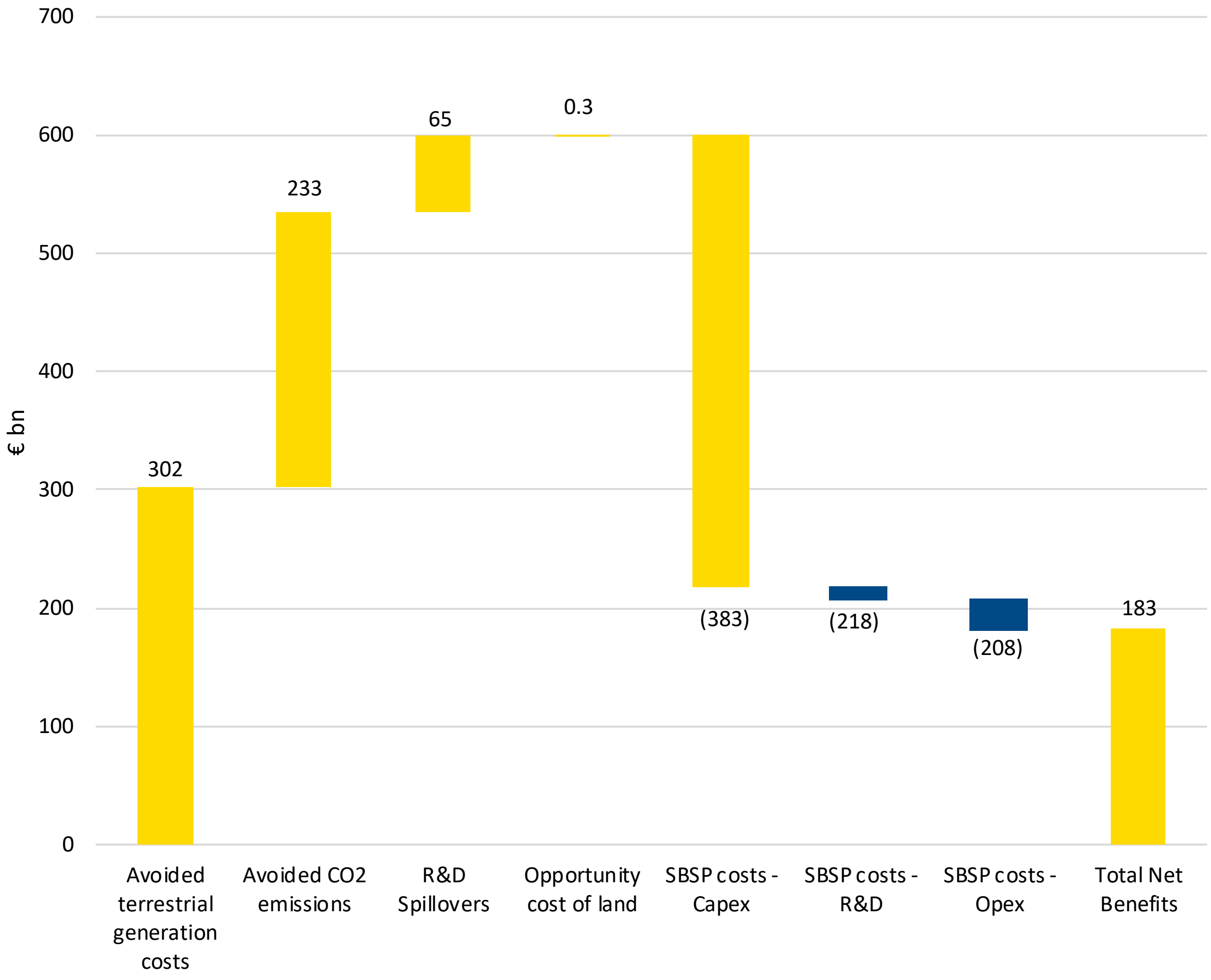
Value driver	**NPV (€ billions)**
(1) SBSP total cost	**(417.9)**
CAPEX (SBSP)	(382.5)
R&D (SBSP)	(10.4)
O&M (SBSP)	(24.9)
(2) Avoided cost of terrestrial electricity generation	***302.4***
(3) Externalities total	***298.1***
CO2 emissions saved	233.2
R&D spillovers	64.5
Opportunity cost of land	0.3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

Source: London Economics analysis

This result is robust to a range of sensitivities, including discount rates, fossil fuel costs, social costs of carbon, and launch capacity. The value bridge (Figure 5) represents all cost and benefits components and their contribution to the total Net Present Value of the system. Although not all costs and benefits can be monetised, the study has adopted a conservative approach to benefit estimation.

Space-Based Solar Power is an innovative concept that can contribute to Europe's efforts in reaching Net Zero. It does so by providing clean baseload power; diversifying Europe's energy sources; improving energy security and reducing the need to import electricity and fuel from abroad; reducing the land needed for clean energy generation, and reducing emissions of greenhouse gases and pollutions.

Figure 5 Value Bridge: Main Net Present Value (NPV) drivers



Source: London Economics analysis

Furthermore, SBSP potentially has advantageous grid integration characteristics, providing both continuous and dispatchable power that are less sensitive to terrestrial weather conditions. Each of these characteristics are essential for maintaining grid stability in a future energy system with a high percentage of intermittent renewables.

SBSP also brings various strategic benefits, such as improved price stability, energy security and independence, as well as potential first-mover advantages for export and spillovers from the R&D associated with development.

The results of the present analysis suggest that the development and launch of SBSP would generate net benefits to Europe and should be explored further.

In fact, sensitivity analyses show that even in the event that all costs of SBSP double relative to the baseline estimates, a launch schedule exists that would yield positive net benefits.

The CBA makes a range of assumptions to estimate costs and benefits, including that Europe will meet the objectives set out to achieve Net Zero carbon emissions by 2050.This assumption is crucial as it implies introduction of SBSP will accelerate that pathway to Net Zero. In an alternative scenario, in which Europe continues along its historical path and fails to reach Net Zero, SBSP generate substantially greater benefits at €767bn.

Concluding Remarks

The findings of this study suggest that SBSP is a potential game changer for Europe and the strong recommendation is to take all necessary steps to develop and implement SBSP. To achieve this, a number of supporting actions are recommended to commence as quickly as possible, summarised below:

- **Develop European launch capacity** to be able to meet the substantial demand for launch services required to bring SBSP into fruition.
- **Update technological feasibility studies and demonstrate technological advancement in key areas** as the results fundamentally depend on the technical capabilities of the SBSP concept. Substantial system studies and technology development should be undertaken to confirm pathways to both technical and economic feasibility of SBSP, and progress in these areas should be digested and incorporated into future cost-benefits analyses.
- **Promote the inclusion of SBSP into Net Zero pathways -** the context of SBSP is a Europe that is moving towards an environmentally cleaner future, with political and technological aspirations that are subject to change. Further discussion, consultation, and projection will help understand the context that SBSP enters.
- **Further explore key cost competitiveness metrics** - this study relied upon the Levelised Cost of Electricity (LCOE) and the Value-Adjusted LCOE as comprehensive measures of cost competitiveness of power generation technologies including SBSP. These measures are relatively new in the literature, and would benefit from further investigation, development, and careful application to the SBSP context.
- **Continued evaluation of benefits -** expanding upon the analysis presented in this study would add information that will likely prove crucial in weighing the ultimate value to European society of the development and construction of such an infrastructure.
- **Explore the potential for taxation policies and/or subsidies** – the suitability of tax/subsidy mechanisms should be studied further to assess their feasibility in encouraging uptake of SBSP in place of fossil fuels and to discourage foreign imports of fuel.
- **Undertake health and safety studies** - SBSP must be seen as a safe technology that will do no more harm than competing technologies to be successful. Any impact the microwave beam, potential space debris, and other health and safety issues must be understood.
- **Start public engagement** - SBSP has been described colloquially as a death ray. A public information campaign must therefore be devised to ensure the population at large buys in to the system.
- **Stimulate international engagement and collaboration -** Europe needs to secure access to the spectrum and orbital slots required for SBSP.
- **Secure funding and explore routes to commercialisation -** funding for the completed SBSP system must be secured. Engagement with public and private stakeholders should help clarify what hurdle rate would be needed to attract private sector participation and the implied level of public sector support. As technical milestones are achieved and uncertainties clarified over time, the high hurdle rates used in this analysis may be revised downwards.
- **Identify suitable rectenna sites and explore permits** - SBSP requires a large contiguous land area for the rectenna. This will need permits in each country and could require expropriation of land. Relatedly, environmental impact assessments will be required on the chosen site. Likewise, rectennas can be co-located with other uses of land (for example agriculture), potentially expanding the range of potential sites where rectennas can be located. The feasibility of this co-location should be explored.
- **Reinforce transmission networks - r**ectenna sites will not necessarily be close to locations of high electricity demand. The transmission network may therefore need reinforcement and interconnectivity.

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