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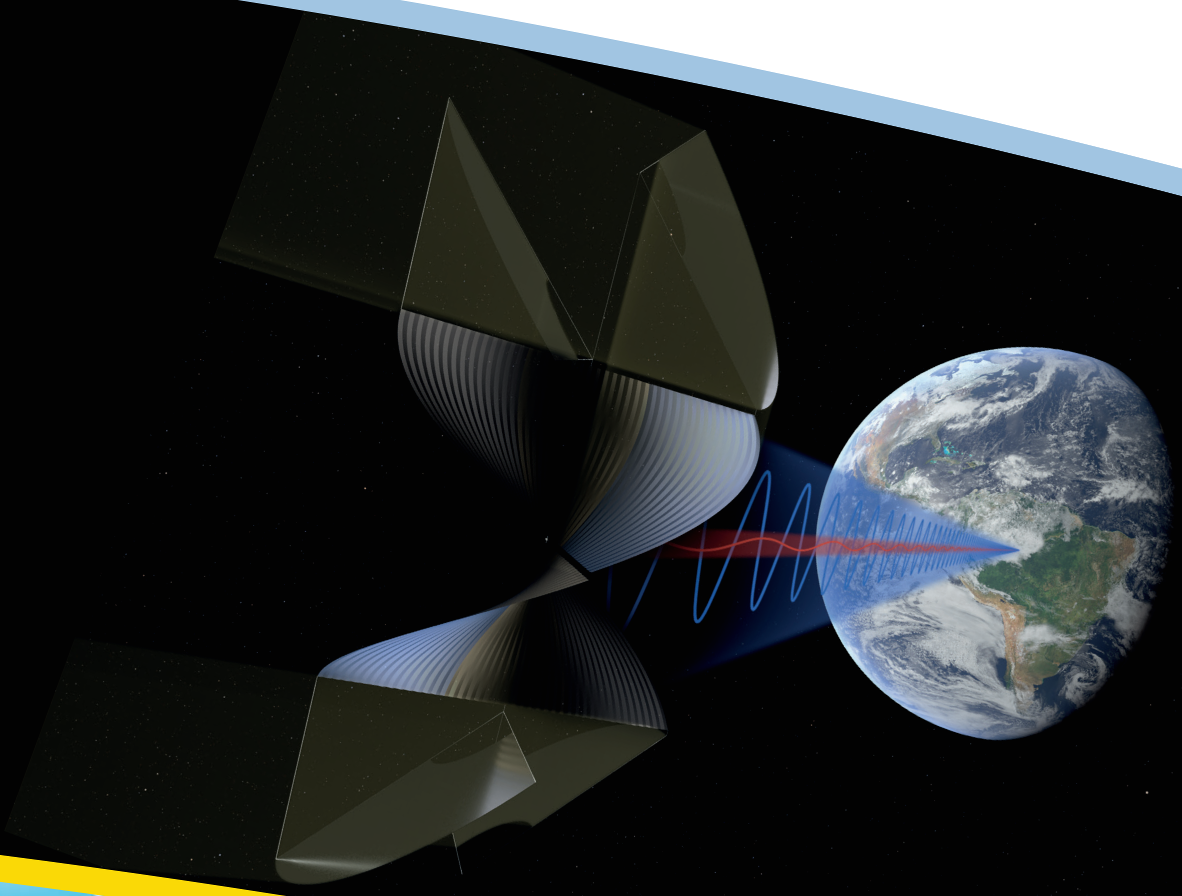
Space-Based Solar Power

A Future Source of Energy For Europe?



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Space-Based Solar Power could de-risk the path to Net Zero in Europe by providing a future source of clean, base-load energy by 2040 or earlier.

R&D investment of
€15,765m
over four phases resulting in a first GW-scale in-orbit prototype[1]

Capital expenditure of
€9.8bn
for first of a kind fully operational system

Potential for
800 TWh
per year by 2050 to contribute to Net Zero

Competitive levelised cost of electricity

Provides energy independence and security

Provides a market for reusable low-cost space launch

De-risks pathway to Net Zero, providing sustainable clean energy that is dispatchable and scalable

R&D investment generates spill over benefits and technological advances

[1] The costs to develop a reusable spacelift capability is not included in the SBSP development programme costs presented here.

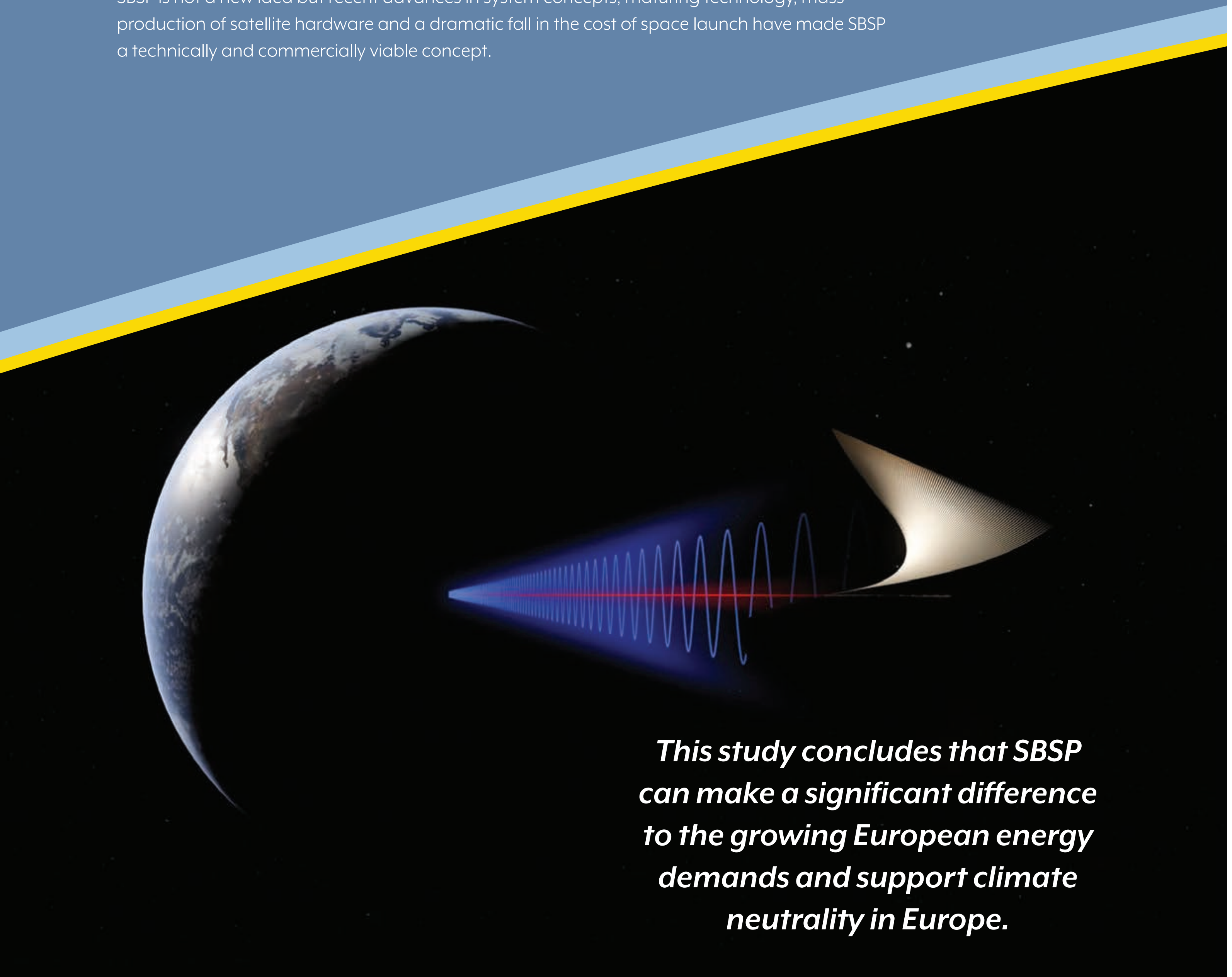
A Significant Contribution to Achieving Net Zero

To achieve Net Zero carbon emissions by 2050, Europe must rapidly decarbonise its sources of electricity generation and ensure both stable and secure supply.

SBSP offers a possible solution: it is a clean base load and scalable source of energy that can offset the intermittency of renewables, provide an alternative to nuclear power, and reduce Europe's energy dependence on other nation states. To deliver SBSP at scale, Europe will need to invest in the technical development of the systems and increase industrial capacity to meet the very large manufacturing and space-lift demand. These investments will be transformational for the space industry and have long-term benefits for Europe at large.

The technical and societal challenges of Net Zero are widely recognised, and new energy technologies are being explored to tackle these challenges. SBSP provides base load dispatchable electricity generation which supports grid stability in an energy mix with a high percentage of intermittent renewable technologies.

SBSP is not a new idea but recent advances in system concepts, maturing technology, mass production of satellite hardware and a dramatic fall in the cost of space launch have made SBSP a technically and commercially viable concept.



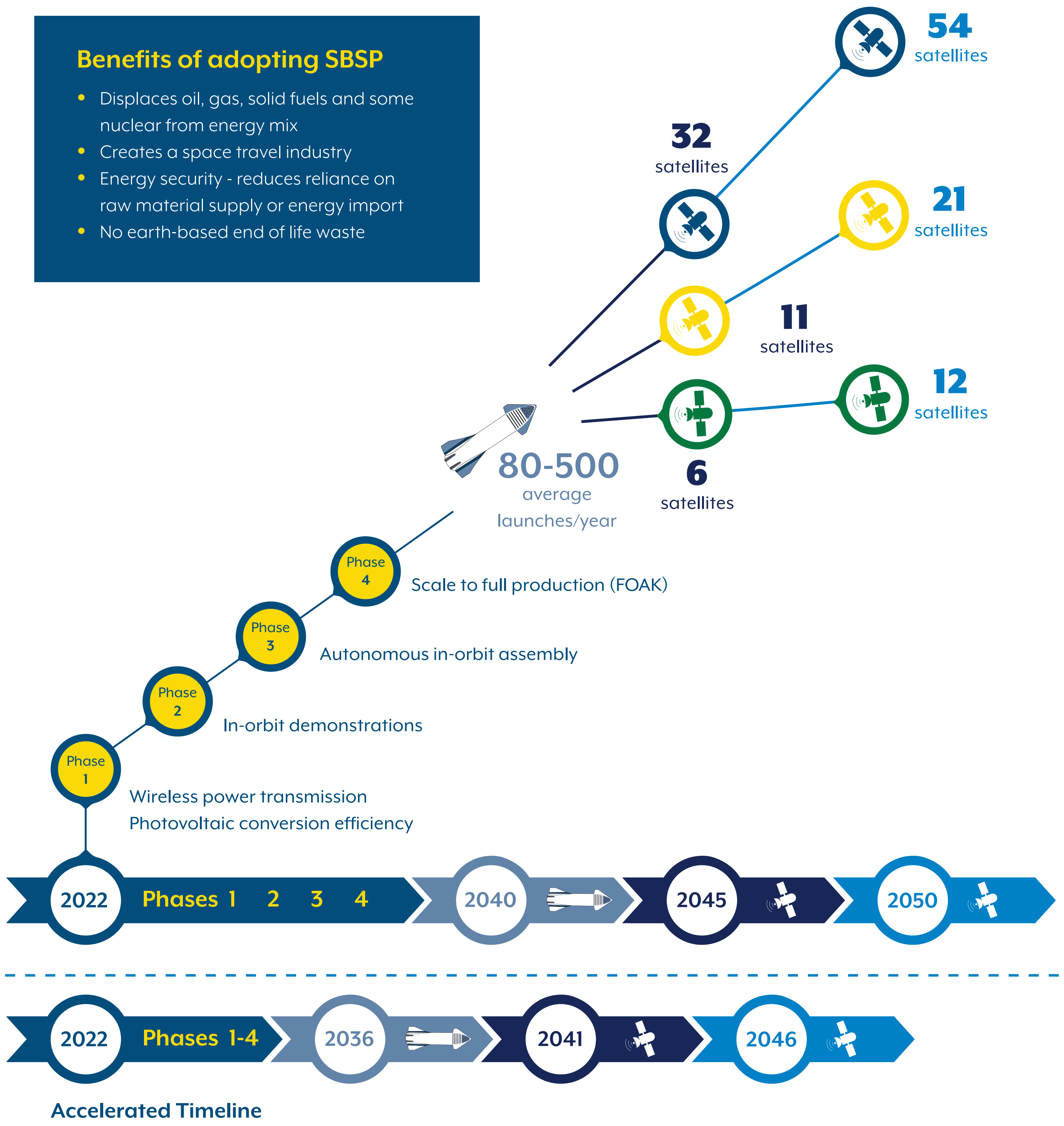
This study concludes that SBSP can make a significant difference to the growing European energy demands and support climate neutrality in Europe.

A roadmap to Space-Based Solar Power in Europe

A fleet of 20 satellites by 2050 would reduce Europe's import dependence in electricity generation to zero.

Benefits of adopting SBSP

- Displaces oil, gas, solid fuels and some nuclear from energy mix
- Creates a space travel industry
- Energy security - reduces reliance on raw material supply or energy import
- No earth-based end of life waste



SBSP can speed up Europe's transition to Net Zero

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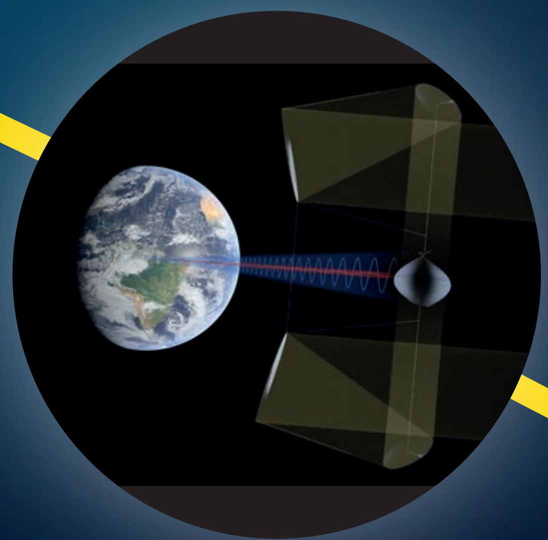
The European Commission has set the target to reach Net Zero by 2050 in order to stay on the path of limiting global warming to 1.5 degrees. However, the route to Net Zero by 2050 is extremely challenging. Electricity generation needs to increase significantly to support the electrification required to replace the need for fossil fuels. Most existing pathways use current or near-term technologies, but even the most technically feasible, cost-effective and socially acceptable pathways all still have shortcomings.

Existing intermittent energy generation technologies (like solar PV and wind) plus storage cannot fully replace the role of baseload and dispatchable energy sources. Continued use of fossil fuel requires technical improvements in carbon capture and storage (CCUS). Nuclear power, while providing a source of low-carbon, base load power, carries long-term issues with decommissioning and security of high-level waste, and national security implications. SBSP offers an alternative to nuclear that can replace fossil fuel power plants, complement intermittent renewables and accelerate the transition to Net Zero by 2050.

SBSP is a technically viable and cost-effective solution to meet Europe's strategic energy needs. It promises significant net benefits (€183bn) if adopted as a baseload energy supply as part of Europe's Net Zero pathway. However, there needs to be significant and immediate investment to advance the technology - technology that will have wide-spread applications like wireless power transfer, which will deliver energy anywhere on Earth without the need for miles of costly infrastructure.



How will Europe benefit from SBSP?

SBSP can beam grid scale power almost continuously, resulting in a unique 'always-on' base load capacity generation from an inexhaustible renewable energy source.

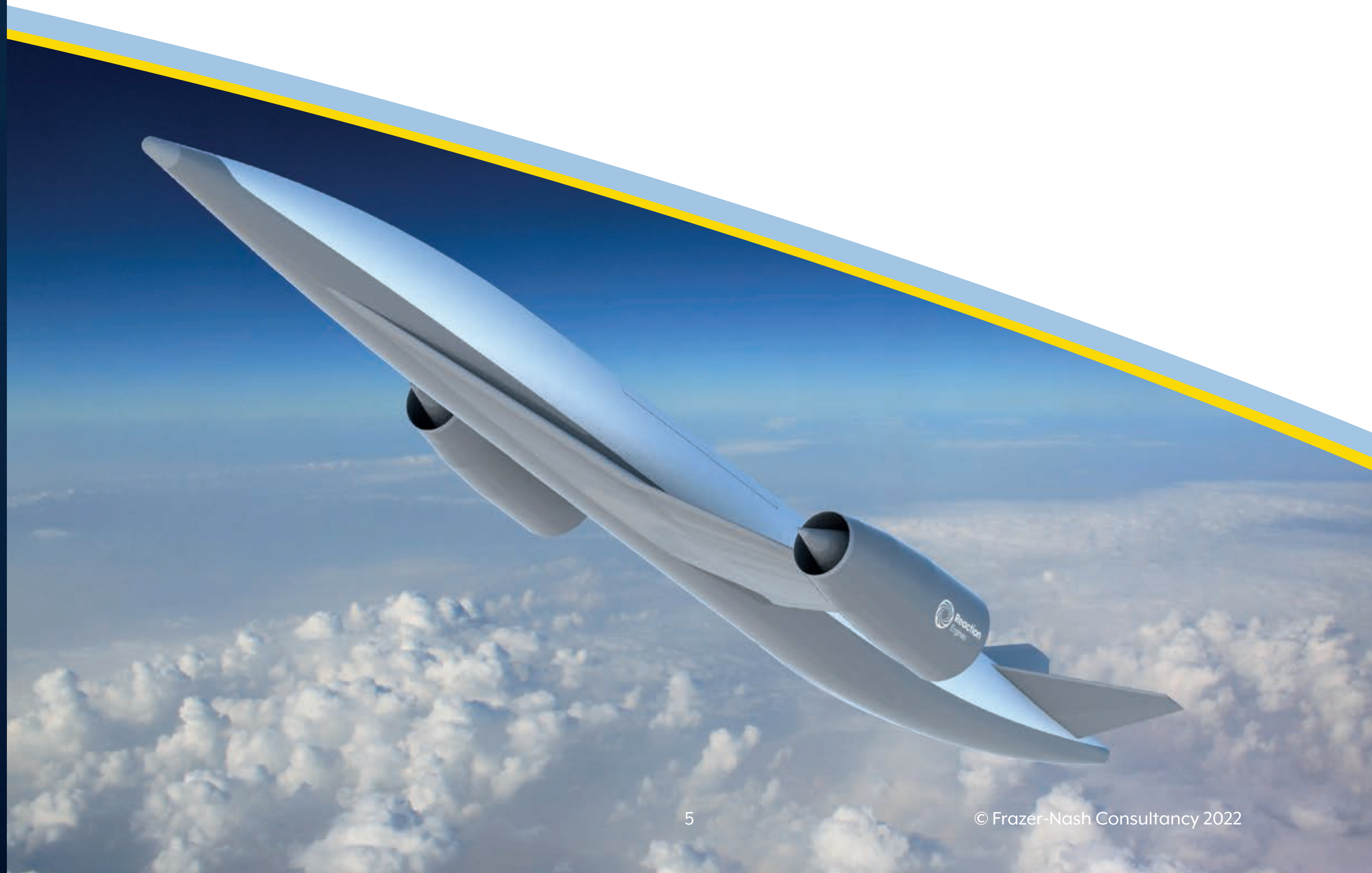
SBSP requires substantial development, but by 2040 it could deliver cost-competitive electricity generation when compared with oil, coal, gas and biomass, and therefore offers a direct replacement. Although nuclear and most other renewables appear to offer lower levelised cost of electricity[2], SBSP could lead to greater long-run benefits.

Economic analysis of the potential for SBSP as a clean, dispatchable, and price-competitive source of electricity to displace alternative sources suggests that meeting the maximum possible demand across Europe would require up to 54 gigawatt-scale satellites to be in operation by 2050.

However, the achievable scale of an operational system will be limited by:

- **Launch capacity** - limitations to the potential cadence of satellite launches to deliver the SBSP system into orbit, given limited launch service capacity
- **Cost and financing** - delays to or failure to finance the large capital requirements of the programme
- **Technological development** - failure of the development programme given the low maturity of SBSP subsystems
- **System build rate** - the large scale of industrial capacity required, limited by availability of land for new facilities, appropriately skilled labour and capital investment
- **Other factors:** socio-political, regulatory, and legal restrictions.

[2] Levelised Cost of Electricity, LCOE, is the most commonly used metric to assess cost competitiveness of power generation technologies. It distils all direct technology costs into a single metric and represents the revenue generated that would be required to recover the costs of building and operating the system during its life.



The benefits of a European SBSP

INCREASED DIVERSIFICATION OF ENERGY SOURCES

SBSP will diversify Europe's energy generation sources making transition to low carbon less risky. SBSP can offer baseload energy that will allow switching off oil and gas plants and enabling transition to intermittent renewable energy sources, establishing a diverse and therefore robust energy mix.

EUROPEAN ENERGY INDEPENDENCE & SECURITY

SBSP will reduce Europe's reliance on the import of gas and other energy generation sources. It offers a potential for Europe to have complete generation independence, and become a net exporter of energy globally. This will provide greater energy security and could be used as a strategic tool to support non-member states.

GRID INTEGRATION

SBSP can provide continuous and dispatchable power that is not sensitive to terrestrial weather conditions, making it a useful asset for maintaining grid stability in a future energy system that has a high percentage of intermittent renewables.

AVOIDED LAND ALLOCATION FOR TERRESTRIAL TECHNOLOGIES

SBSP will be a land-efficient generation technology, using only 5m^2 of land per MWh, far less than most alternatives. And the rectenna - its largest footprint could be co-located with other productive purposes, like agriculture, reducing its impact further.

ELECTRICITY PRICE STABILITY

By reducing its reliance on energy imports Europe will be less vulnerable to price increases from external international events. Moreover, SBSP in particular will reduce the continent's exposure to raw material price fluctuations – and especially so compared with other energy generation technologies that are dependent on scarce raw minerals that cannot be sourced from Europe.

R&D SPILLOVER & TECHNOLOGICAL ADVANCEMENT

The pursuit of SBSP technology will unlock technology and knowledge that can create new products and markets to enhance people's lives. Wireless power transfer, improvements in space-lift, and in-orbit robotic assembly are likely to spill over into other domains and used in other applications in space and on Earth.

NEW EXPORT OPPORTUNITIES

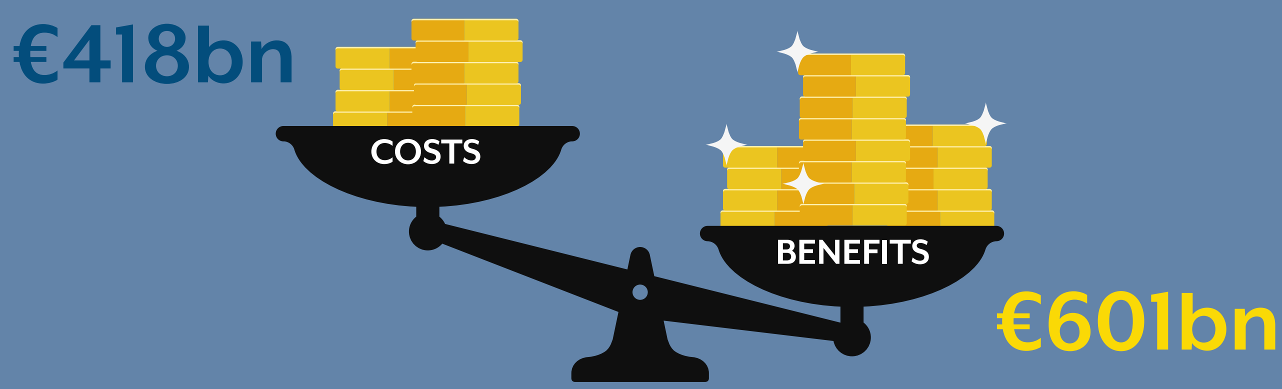
The predictability of domestic SBSP energy generation could significantly increase export potential. Energy could be sold to economies outside Europe, leading to more import revenues and reversing the current situation.

AVOIDING CO_2 EMISSIONS AND OTHER POLLUTANTS

SBSP will reduce the reliance on fossil fuels to generate electricity. There will be no need to mine raw materials for generation, other than to make the satellites, and no harmful waste leftover. SBSP can produce thousands of TWh's of truly sustainable electricity.

The Net Present Value of quantified benefits between 2022 and 2070, for the base case scenario - which is the agreed and legally binding Net Zero pathway that Europe's countries have committed to in the Paris Agreement - is estimated to lie in a range between €149bn to €262bn with the central case value of **€183bn.**

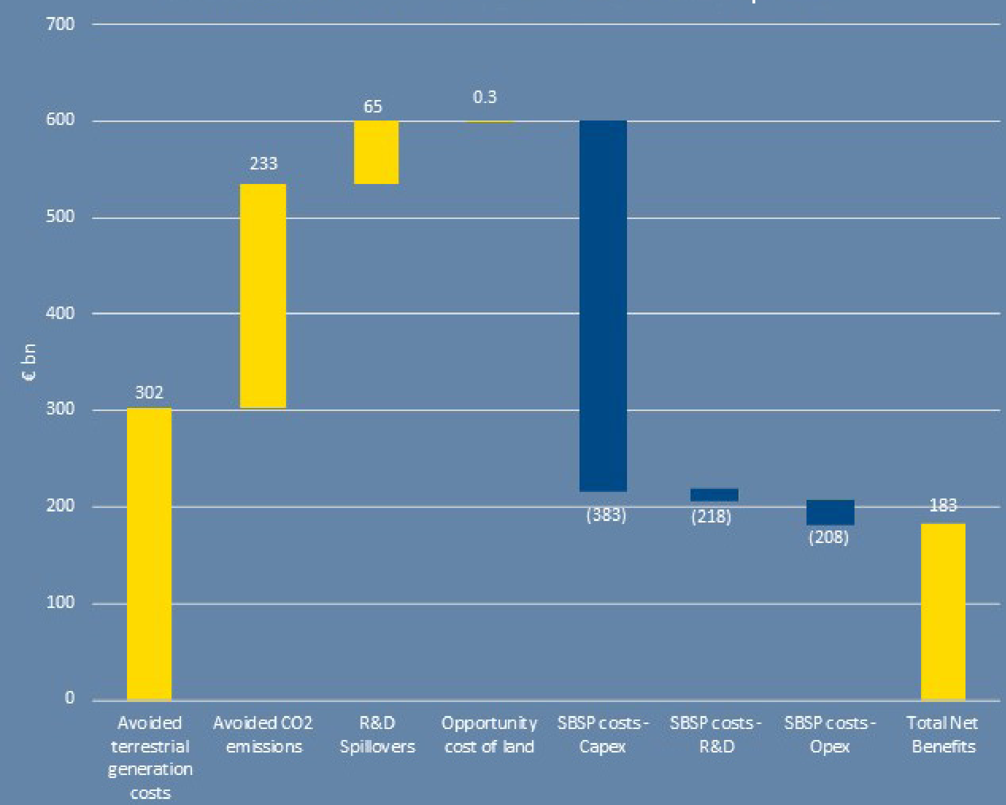
This is the sum of SBSP costs for 54 satellites by 2070 estimated to amount to €418bn and the SBSP benefits of €601bn.



SBSP benefits include:

- Avoided cost of terrestrial technologies
- Avoided social cost of CO_2 emissions
- Spill over benefits from R&D spending
- Opportunity cost of land

Net Present Value Cost and Benefits of European SBSP



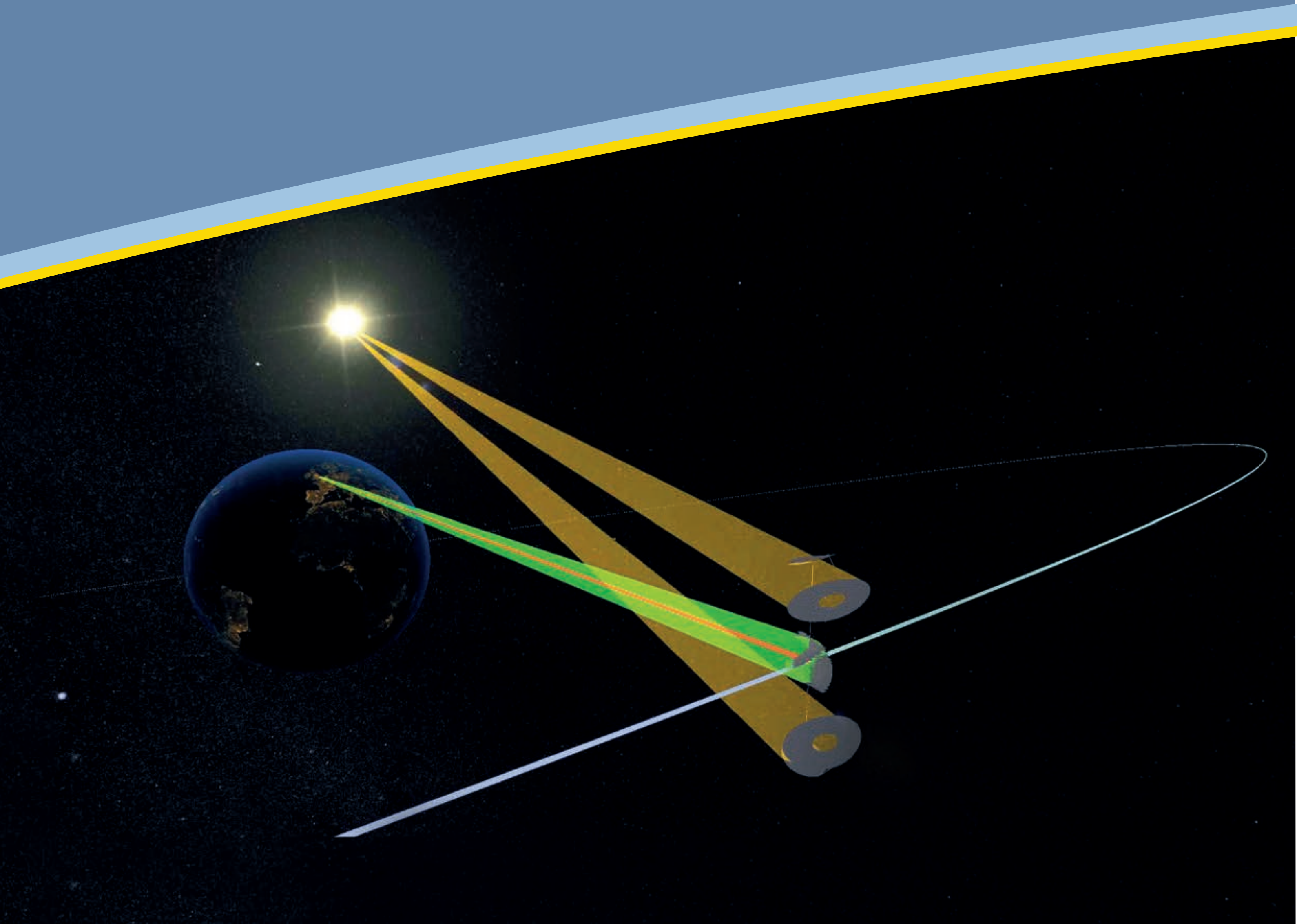
How does SBSP work?

Space-Based Solar Power is the concept of collecting solar energy in space using very large satellites.

These satellites would typically be 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), where the electricity is generated by a large rectenna. A typical single satellite could provide between 1 GW and 2 GW of power continuously.

Satellites in GEO are illuminated by the sun for more than 99% of the time, with a solar intensity substantially greater than received on the ground. This feature underpins the main advantage of SBSP as an alternative energy source. Compared to wind and solar power, SBSP can deliver energy day and night throughout the year, and in all weathers. SBSP is scalable and could make a major contribution to the global need for abundant, affordable clean energy.

Integration of SBSP into the electricity generation system consists of a research and development phase, followed by the deployment of the first operational satellite, and the operational phase, when new satellites will be added to the system to scale up the generation capacity.



How much will it cost?

The first SBSP system to be put into service is estimated to cost €9.8bn in 2022 prices and have operational costs of €3.5bn through its 30-year life.

Due to economies of scale subsequent systems are cheaper. The cost of the tenth system is estimated to be €7.6bn with operational costs of €1.3bn. This equates to a conservative estimate for the levelised cost of electricity at €206/MWh for a FOAK and €156/MWh for the tenth system, making it competitive with all leading low-carbon energy generation sources.

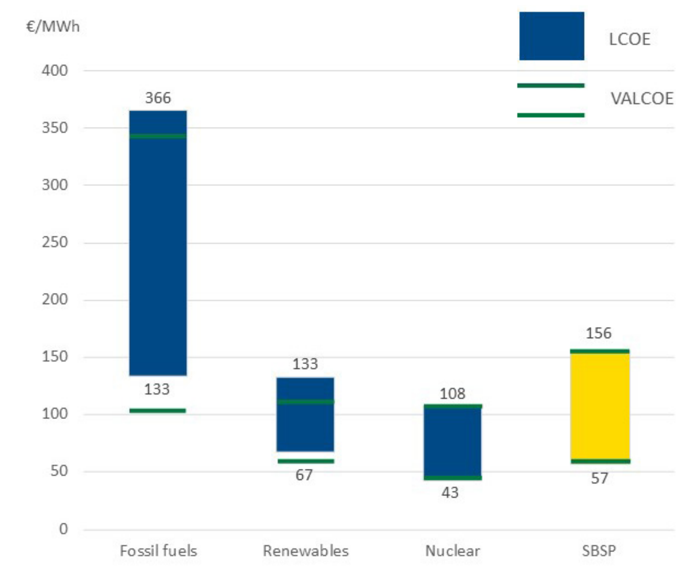
Once the technical risks of SBSP are mitigated — for example, following a successful development programme resulting in a full-scale in-orbit demonstrator — investors might set a financial hurdle rate that becomes comparable with alternative forms of base-load energy.

At a 10% hurdle rate, the LCOE of the first SBSP system is comparable with a nuclear new build programme (€109/MWh versus €108/MWh respectively).

At a 5% hurdle rate, the LCOE of the first system would be €69/MWh, making it more cost-competitive than all alternatives.

"The cost of the tenth system is estimated to be €7.6bn with operational costs of €1.3bn."

A comparison of SBSP vs other energy generation types



Capex and Opex for first and tenth SBSP

"Investors might set a financial hurdle rate that becomes comparable with alternative forms of base-load energy."

Spacelift capacity needs to increase to meet SBSP launch requirements

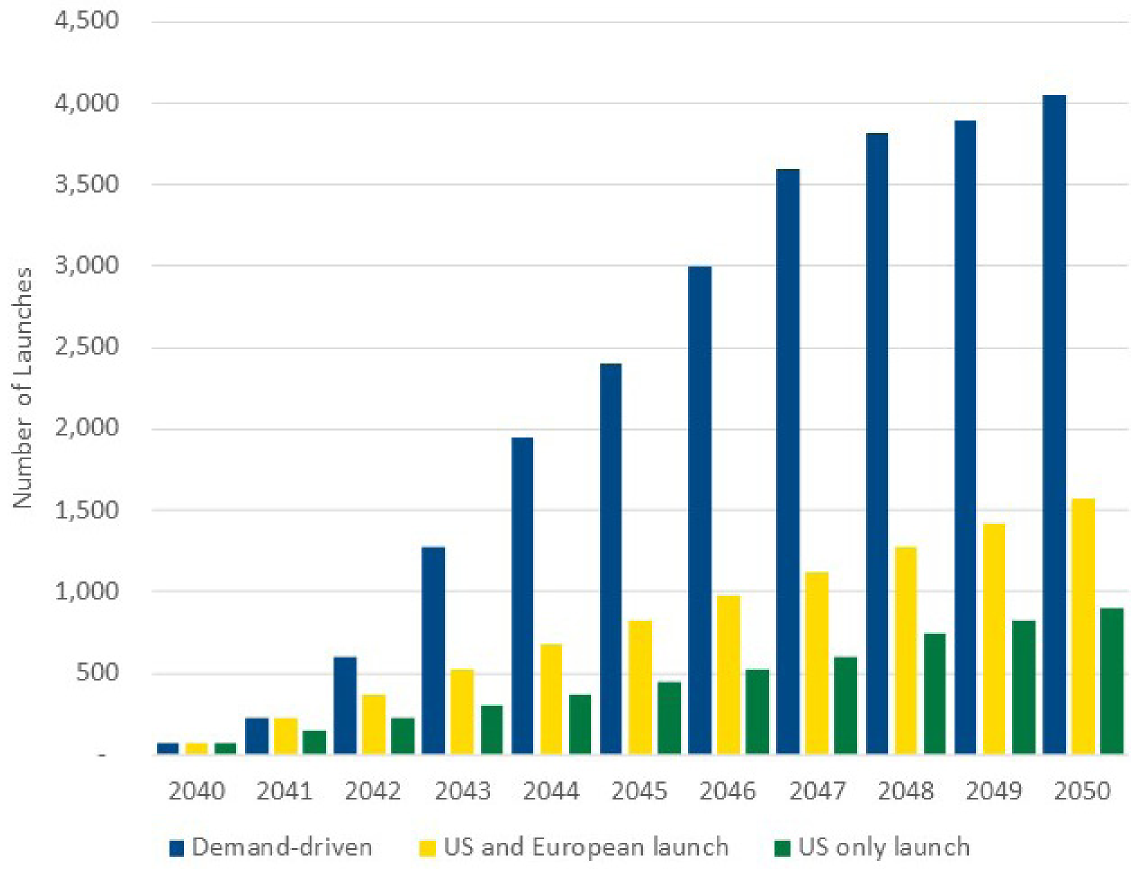
Availability of space launch capacity will be a key constraint to the timing and speed of SBSP deployment.

Using projected near-term space lift capability, such as SpaceX's Starship, and current launch constraints (based on the number of permitted launches and existing demand for space-lift capacity) delivering one satellite into orbit would take between 4 and 6 years. Providing the number of satellites to satisfy the maximum contribution that SBSP could make to the energy mix in 2050 would require a 200-fold increase over current space-lift capacity. By doubling the number of suitable launch sites and lift cadence, a 16-fold capacity increase can be achieved. Significant investment in new space-lift sites and launch vehicles will be needed.

A European space-port and one reusable heavy launch vehicle could support around 77 SBSP launches per year, sufficient for an additional satellite per year to be delivered, taking global systems to between 1.5 and 2 per year. At that cadence, by 2050 there could be no more than 20 SBSP satellites, less than half the theoretical maximum.

The pursuit of a European SBSP system will create demand for hundreds or potentially thousands of launches per year (depending on future scenario), which will support a commercially sustainable market for a low-cost, reusable launch capacity in Europe.

Cumulative Launches by Scenario



Future Spacelift Scenarios

- **US launch only** – assumes no additional increase in current spaceport capacity globally
- **US & European** – assumes a new European owned spaceport to double capacity
- **Demand Driven** – a theoretical maximum demand for SBSP based on assumptions of alternative energy sources that it offers greater net benefits and so can displace in future Net Zero scenarios.

What would a European SBSP development programme look like and how could it be funded?

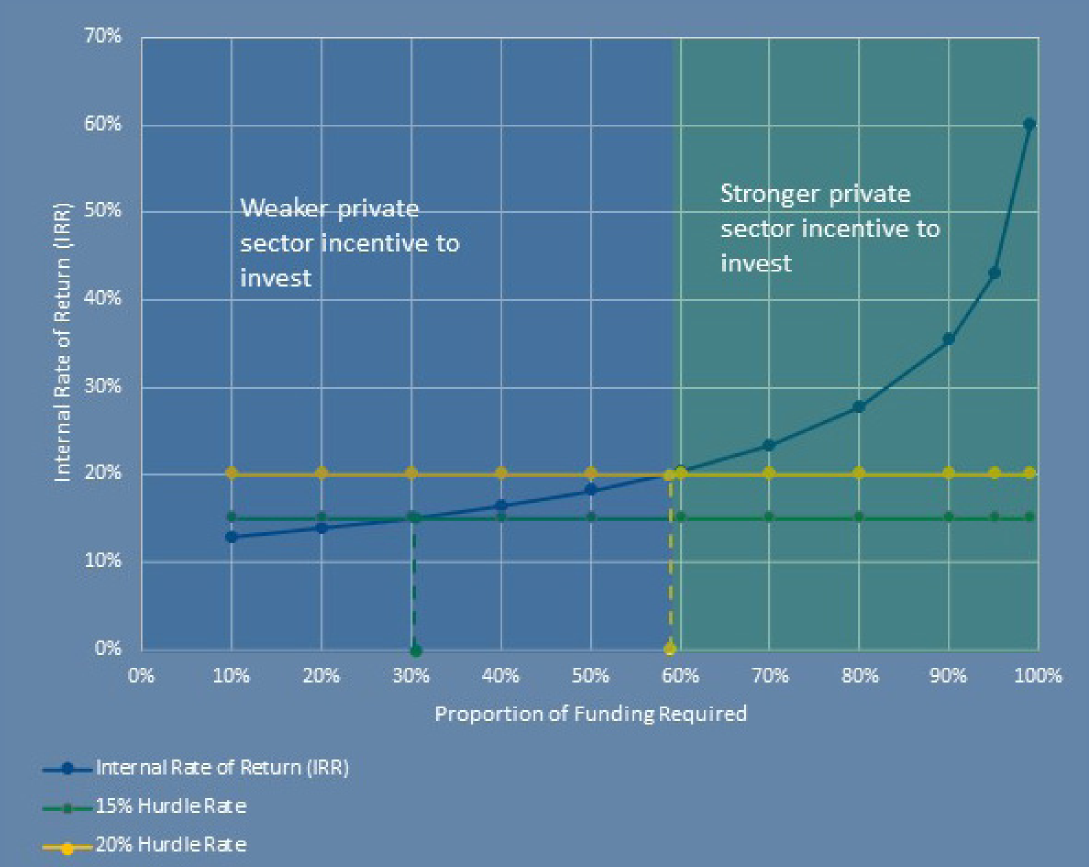
A SBSP system could be developed through a four-stage programme designed to mature the technologies through a series of increasingly large and complex prototypes.

The phases would comprise development design and system testing, initial in-orbit demonstrations, full system in-orbit demonstrations, and production level scale-up, leading to a full-scale pre-production operational prototype. An 18-year development phase for SBSP, based on engineering judgement of the pace at which milestones could be reached, but this could be shortened with sufficient investment, greater risk acceptance (or reduced delivery risk), and a political will that includes the pursuit of SBSP in future Net Zero energy pathways.

A new energy generation technology programme is characterised by a technically challenging development phase which carries significant delivery risk and high up-front capital costs, followed by back-ended financial payback. This creates significant funding and financing challenges.

The risk profile means that Government public funding will be required to initiate the development programme. Based on a 20% hurdle rate, public funding will be needed for up to 58% of the development costs. Lower hurdle rates will require lower public sector contribution, reflecting the lower risk and thus greater private sector interest in investing early in the programme. At a 15% hurdle rate, the contribution of the public sector contribution to bridge the investment risk gap is only 30% or €3 billion with a requirement of co-leveraged private investor funds of circa. €7 billion. A reduction in perceived risk and high cost of capital has a significant effect on the public/private sector funding split.

Public Funding Thresholds



SBSP for UK

The United Kingdom has ambitions to become a global leader in decarbonisation, with ambitious targets for emissions reductions such as the Low Carbon Transmission Plan launched in 2009, long before the nation hosted COP26 in late 2021.

In 2019 the UK became the first major economy in the world to legislate for a legally binding Net Zero target. Despite this target, the UK is still heavily reliant on fossil fuels including coal, oil, and gas, and is a net importer of both electricity and energy as a whole, despite a long history of being a net exporter of petroleum products.

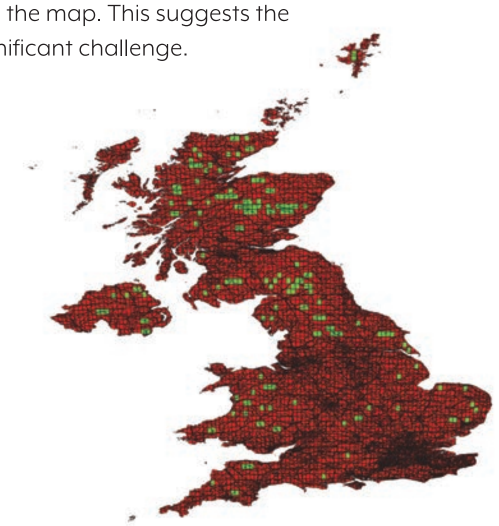
To meet Net Zero, the UK's planned and required investment in intermittent renewables is significant. While the nation has plenty of available land and sufficient demand to sustain renewables, in particular onshore and offshore wind, these sources come with associated uncertainty and requirements for battery storage. SBSP is uniquely able to provide clean baseload power on a scale that would allow the UK to further reduce its dependence on fossil fuels, generate low-carbon 'green hydrogen', and sidestep some of the issues of weak solar supply on the road to achieving the nation's Net Zero target.

SBSP could be a potentially valuable addition to the UK's option set as it drives toward achieving Net Zero. It could reduce the reliance on intermittent renewables, which are modelled to make up over two thirds of the UK's 2050 electricity supply in the Net Zero scenario. While energy storage using batteries can reduce the variance and hence issues here, SBSP offers another source of baseload power that does not require fossil fuel usage or greater expansion of nuclear generation.

Using estimates of the output per SBSP satellite and assuming that SBSP could replace all oil, natural gas, coal, 15% of new-build solar and wind capacity, and 15% of new nuclear capacity between 2040-70, we estimate an implied satellite demand that grows from 5 in 2040 to around 10 in 2070.

The landmass required for SBSP rectennas per MWh in the UK (5.9 m^2/MWh) would be substantially less than that which is required for solar PV (13-22 m^2/MWh) or onshore wind (99 m^2/MWh). A high-level multi-criteria GIS analysis on spatial data for roads, waterways, urban areas and national parks identified around 160 locations with the necessary geographic dispersion for siting rectennas in the UK, with more in the off-shore locations, as indicated by the green locations on the map. This suggests the identification of a suitable location for SBSP in the UK would not pose a significant challenge.

The net benefits to the UK of introducing SBSP satellites according to this demand are €93bn over the 2040-2070 period in present value terms.



Study commissioned by the European Space Agency.

Delivered by Frazer-Nash Consultancy
in partnership with London Economics.