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SPACE SOLAR

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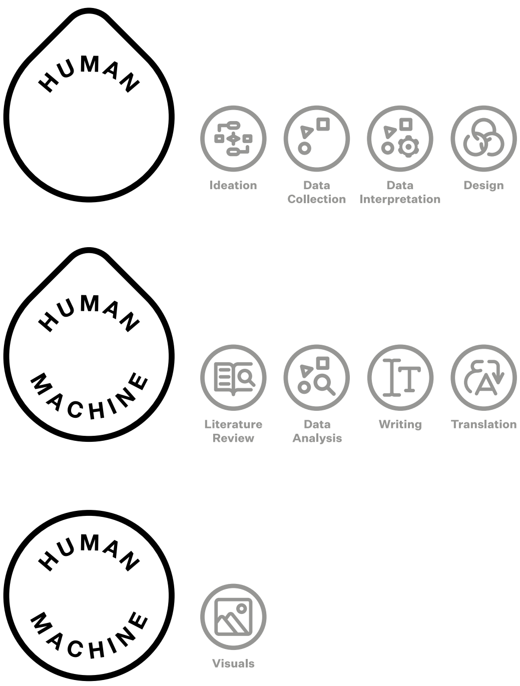

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Executive Summary

Space-based solar power (SBSP) – the concept of capturing solar power in space and transmitting it wirelessly back to Earth – has gained the attention of governments around the world. It is a potential solution to meet future global energy needs, and the European Space Agency notes that a single solar satellite could generate approximately 2 GW of uninterrupted power, equivalent to a conventional nuclear power plant.[1]

Several countries and regions, are already exploring future SBSP to meet increasing global energy needs. If technological research, development, and demonstrations proceed as planned not only in Europe but also by China, Japan, the United Kingdom, Europe, and the United States, along with private sector players, kilowatt-scale orbital demonstrations (China, Japan, and the United States) will be a reality within five years (2025–2030), megawatt-scale pilot plants within 10 years (2030–2035), and the first commercial gigawatt-scale power satellites within 15–25 years (2040–2050).

SBSP consists of five core technologies: launch systems, on-orbit assembly, solar power capture, power transmission, and ground receiving stations. With advances in artificial intelligence, solar panel technologies, materials science, reusable rockets, and wireless power transfer, SBSP is likely to become a part of our near future.

This report examines the current state of SBSP technology and its potential as a solution to meet growing global energy demands while supporting decarbonisation commitments. In addition to investigating the 'why' of SBSP, we carried out interviews to unpack the technological readiness of key SBSP components, evaluate the international landscape of government policies and initiatives, and take into account key considerations for policymakers as they explore the potential of this future technology.

With industries becoming increasingly energy-intensive, the realisation of SBSP pilot plants in orbit will mark a significant step towards access to abundant and clean energy. This will likely shift the entire energy landscape.

1

Introduction to Space-Based Solar Power

The global energy race is accelerating as countries around the world ramp up efforts to identify scalable energy sources. Because of volatile energy markets, rapidly growing energy-intensive industries, and net-zero commitments (see Box 1), policymakers have realised that existing energy sources are both economically and environmentally unsustainable. Although initial optimism for alternative energy sources – such as geothermal, hydropower, nuclear, solar photovoltaics (PVs) and wind energy – generated significant investment, it is now clear that such sources cannot yet respond to large-scale energy needs as they face challenges related to scalability, storage, and transmission.[2]

BOX 1

Decarbonisation

A core motivation driving the momentum behind SBSP initiatives is the global policy focus on decarbonisation and net zero goals. As the energy sector is the largest contributor to global emissions, it is widely considered to be the most urgently in need of decarbonisation.[3] In this context, the globally accepted pathway to decarbonisation is through the gradual electrification of energy use and a transition to 100% green electricity sources. Between today and 2050, global electricity demand is expected to triple to approximately 70,000 TWh annually, with 90% coming from renewable sources. While this pathway includes scaling up of solar and wind capacity, currently accounting for around 10% of global electricity generation, these sources (combined with biofuels, geothermal, and hydropower) are expected to meet only two-thirds of total electricity needs. As a result, alternative large-scale energy solutions such as SBSP have gained attention as credible solutions for global decarbonisation.[4]

Space-based solar power (SBSP) – the concept of collecting solar power in space and transmitting it wirelessly back to Earth – has gained the attention of governments around the world as a potential solution to meet future global energy needs. Although ambitious, the concept is an application and scaling of existing technologies and does not require any scientific breakthroughs.[5] Indeed, the United States' National Aeronautics and Space Administration (NASA) first explored SBSP in 1970 and found that, although prohibitively expensive, it was technologically feasible even then.[6] Recent advances in technology leading to cheaper launches[7] have improved the economic viability of SBSP and the industry is rapidly gaining momentum. Governments and entrepreneurs are racing to develop the technology, with agencies from China, European Space Agency, Japan, the United Kingdom, and the United States launching large-scale SBSP initiatives; number of critical milestones are scheduled for the next few years: Japan Space Systems and the US Air Force in 2025[a] followed by China in 2026[8, 9, 10] and private sector companies Space Solar and Virtus Solis in 2027. If these are successful, multi-megawatt pilot plants will be sent into orbit in the next five years.

Space Based Solar Power as a Future Opportunity

UNCERTAINTIES

Collaboration

Nature

TRENDS

Most significant megatrend:
Energy Boundaries

International Collaboration

New Materials

Net Zero

Space Economy

Advanced Connectivity

TECHNOLOGIES

Space Technologies

Sensor Technologies

Next-Gen Energy

SECTORS IMPACTED

Automotive, Aerospace & Aviation

Energy, Oil & Gas, & Renewables

Financial Services & Investment

Infrastructure & Construction

Utilities

KEYWORDS

Energy

Satellite(s)

Solar Photovoltaics (PV)

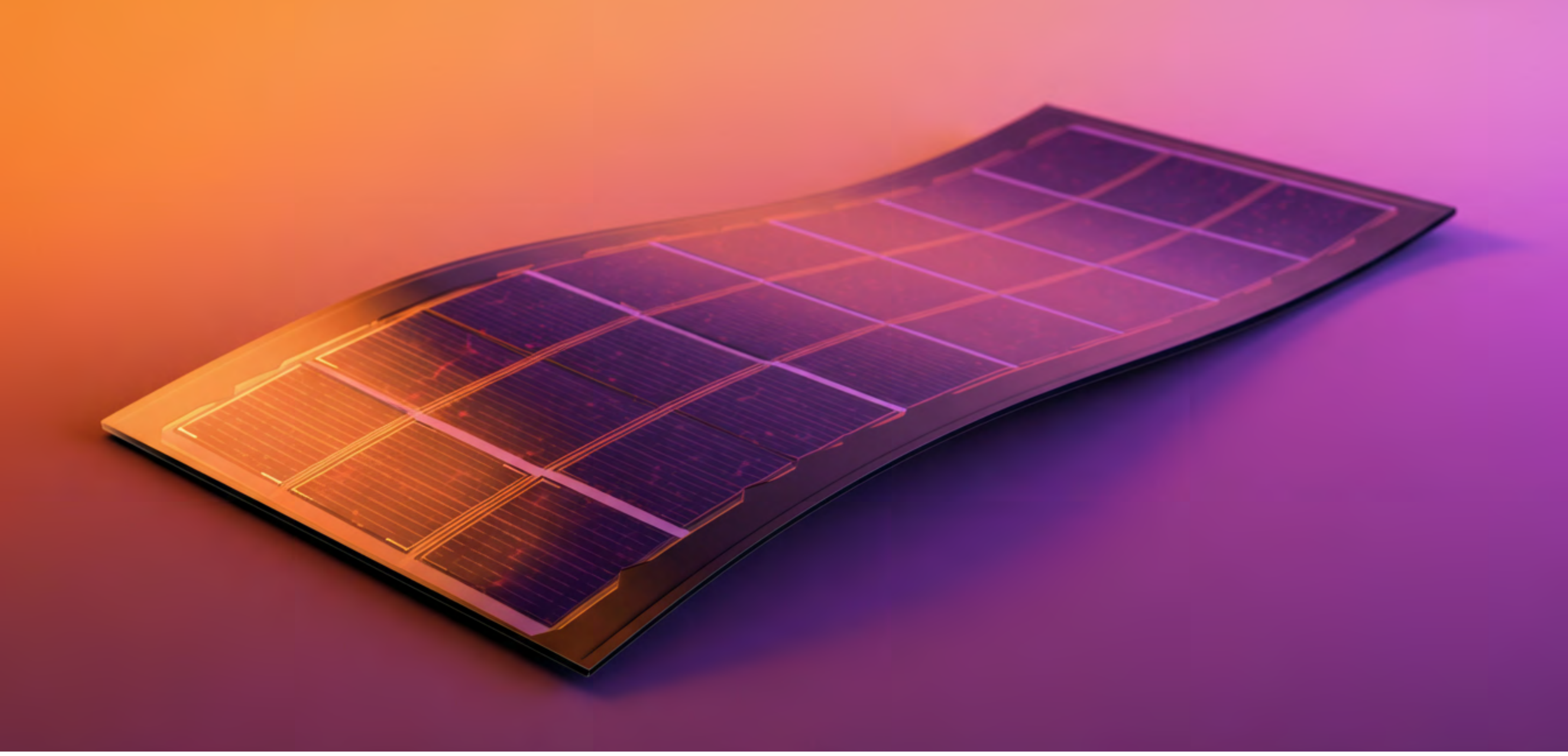
Space Power

Transmission

[a] Based on the latest publicly available information available at time of publication

2

THE PROMISE OF SPACE-BASED SOLAR POWER



The case for SBSP is grounded in its promise of constant and limitless clean energy. Capturing solar power through satellites in space is vastly more effective than collecting it on the ground because of the absence of day/night cycles, seasonal variations, and local weather and atmospheric attenuation effects – not to mention the simple fact that the site of capture is closer to the sun.[11] The result is a predictable, continuous, and high-intensity solar flux (the amount of solar radiation received per unit area of a given surface or material).[12]

When it comes to energy capture, SBSP is a potentially scalable source of baseload power, meaning that it is an 'always on' energy supply that is capable of consistently meeting the minimum requirements of the electricity grid. It offers advantages over ground-based solar and wind, which require vast backup and storage solutions to balance their intermittency[13] (i.e. they only produce electricity when sunlight or wind is available). This intermittency makes it challenging for power system operators, who, as the share of variable renewables rises, cannot ensure that there will be enough power at the time it is needed or cannot maintain frequency and voltage. For example, countries and regions with high wind and solar penetration, such as Germany and California (USA), have experienced grid instability and the need to curtail excess generation. Integrating large shares of renewables thus demands significant investment in upgrading in grid infrastructure, energy storage, and flexible backup generation.[14]

Although other clean energy solutions, such as hydropower, nuclear fission, and to a lesser extent geothermal and wave power, could provide baseload supply, they also face a number of challenges in achieving scale (see Box 2).

BOX 2
Challenges in Scaling Renewable Energy

It is widely argued that scaling renewable energy such as solar, wind, and geothermal faces a number of technological and economic challenges.

- **Intermittency and grid integration:** Solar and wind power are intermittent energy sources, i.e. they only produce electricity when sunlight or wind is available. This variability makes it challenging for power system operators who, as the share of variable renewables rises, cannot ensure that there will be enough power at the time it is needed or cannot maintain frequency and voltage.[15]

- **Geographical constraints:** The best renewable resources are not evenly distributed. Wind and solar farms must often be built in remote areas, far from the population centres where the energy is needed. Additionally, geothermal energy is site-specific – it requires high heat flow areas (often near tectonic plate boundaries) and extensive drilling.[16] This means that renewable expansion is sometimes constrained by location – abundant potential in one region cannot easily supply another without extensive transmission lines.

- **High upfront capital costs:** Building renewable energy infrastructure requires substantial initial investment. Geothermal plants, in particular, have very high upfront costs for drilling and specialised equipment, making them capital-intensive and risky for investors.[17] While solar panels and wind turbines have seen dramatic cost declines, utility-scale projects still involve large outlays for site development, grid connection, and energy storage. Financing these projects can be challenging in markets without stable policy support.[18]

- **Transmission infrastructure limitations:** Scaling up renewables is tightly linked to expanding transmission grids. Currently, nearly 1,500 GW of planned wind and solar projects worldwide are waiting for grid connections because of insufficient transmission capacity.[19] Without new power lines to carry electricity from new solar and wind farms, projects are often backlogged or curtailed.[20]

Beyond intermittency, renewable energy sources pose other challenges related to energy storage (see Box 3). While these challenges are not unique to renewables, they can be avoided via SBSP.

BOX 3
The Challenge of Energy Storage for Renewables

The ability to store excess solar or wind energy is critical and remains a major barrier to scalability because of the variability of the energy supply.

- **Technological limitations:** Currently, there are only a limited number of technologies that allow renewable energy storage, including pumped hydroelectric storage, hydrogen energy storage, and lithium-ion batteries.[21, 22] However, each of these storage solutions has its own challenges caused by geographical constraints, conversion inefficiency, and materials supply issues.

- **Cost:** Storing energy at scale remains notably expensive. While battery costs have fallen sharply over the past decade, deploying enough batteries to back up a grid for many hours or days is costly.

For example, one of the world's largest battery installations – Nova Power Bank in California – is able to power about 680,000 homes for up to four hours when charged, at a cost of $1 billion.[23, 24]

- **Short-duration focus:** Most storage solutions available today are suitable for short-duration applications, with long-duration storage proving a difficult challenge. Most regions still rely on fossil fuel plants during periods of low renewable energy production and energy shortfalls.[25]

- **Alternatives still at an early stage:** Although researchers are actively exploring solutions such as advanced flow batteries and power-to-gas (hydrogen or ammonia), these technologies are only in the pilot stage and not yet widely deployed.

When it comes to energy transmission, SBSP also offers the critical advantage of being highly dispatchable, as SBSP satellites can be positioned in a geostationary orbit and deliver energy to different locations on Earth when the direction of the beam is changed. SBSP satellites can therefore supply energy to users in locations currently geographically distant from energy grids, such as users in remote areas of Europe and in Africa, eliminating the need for costly and sensitive transmission lines (see Box 4).[26]

SBSP technology would enable an inexhaustible clean energy source, allowing countries to augment their existing energy mix.

BOX 4
The Challenge with Scaling Energy Transmission

Energy transmission, essential for both renewable and conventional energy systems, is the critical enabler that connects energy supply with demand. However, there are critical challenges with expanding the transmission infrastructure, the least of which is that building and upgrading transmission lines is capital-intensive and requires years of construction. Overcoming the challenges of cost, permitting, and infrastructure ageing in transmission will yield benefits across the entire energy system, making this a critical issue for energy policy in the coming decades.

- **Investment gap:** Globally, investment in transmission and distribution needs to roughly double, to over $600 billion per year by 2030, to accommodate expanding electricity demand and bring new generation sources online.[27]

- **Reliability and resilience:** Transmission resilience against storms and heatwaves is of universal concern. Indeed, the majority of large blackouts are caused by transmission or distribution failures, often induced by the weather.[28]

- **Security threats:** The energy transmission infrastructure is increasingly a target of cyberattacks. Examples include the 2015 attack on Ukrainian power companies, including substations;[29] the Colonial Pipeline cyberattack in 2021, which temporarily halted the supply of gasoline to much of the east coast of the United States;[30] and the 2022 attacks on electricity substations in North Carolina (USA).[31] Protecting of infrastructure against these risks, through grid redundancy, undergrounding of lines, and enhanced surveillance, is a growing priority.

- **Environmental impact:** The installation of transmission lines should also consider local environmental sensitivity. For example, a line through a forest might fragment habitats and, if not maintained, power lines can spark wildfires (as has happened with some wildfires in California). Thus, operational practices (such as vegetation management under power lines) are important to prevent environmental damage, which in turn causes energy disruptions.

> “Overcoming the challenges of cost, permitting, and infrastructure ageing in transmission will yield benefits across the entire energy system, making this a critical issue for energy policy in the coming decades.

3

WHY SPACE-BASED SOLAR POWER IS GAINING MOMENTUM NOW

Although leading space agencies have been exploring the promise of SBSP technology for decades, SBSP is rapidly gaining momentum because of two recent trends:

1. **Technological advances in space technologies and, as a result, economic viability**

2. **The push to identify scalable energy sources to address energy security, climate concerns, and commitments.**

Together these factors are driving renewed urgency and interest in the technology and bringing SBSP to the forefront of global innovation.

One of the key technological advances that has improved the economic viability of SBSP is visible in the launch industry. After staying relatively constant since 1970, **launch costs** fell dramatically in 2010 after the commercialisation of cost-effective reusable rockets such as SpaceX's Falcon 9. Launch costs have dropped from $20,000 per kilogram in 1970–2000 to $1,400 per kilogram in 2018, rapidly diminishing one of the key constraints that historically inhibited the economic feasibility of SBSP.[32] Increasing private sector competition in the launch industry and further technology advances suggest that launch costs are likely to continue to decline in the near term. Indeed, SpaceX's Falcon Heavy rocket is expected to further reduce the cost of launch to $1,000 per kilogram.[33]

Additionally, **solar panel technology** for space applications has improved drastically because of a number of key advances. Incumbent technology for space solar cells, which use gallium arsenide and germanium, is notably expensive and limited the potential scale of SBSP structures. However, new innovations in this industry have led to the development of radiation-hardened silicon solar cells, which can provide long-lasting and notably cheaper space energy collection solutions and are resistant to degradation in space. Solestial, a private sector firm that manufactures space-stable silicon PVs, is currently providing radiation-hardened solutions with 90% lower cost than the incumbent multi-junction solar products.[34]

Wireless power transfer (WPT) technology, through which the solar power collected in space can be beamed back to Earth, has also seen significant improvements in efficiency, further accelerating the momentum around SBSP. Microwaves are generally considered safest option to use, as their rays are least likely to have adverse effects on animals and plants unless directed at a single animal or plant for an extended period. They are also resilient to adverse weather conditions, such as clouds, rain, or fog. Stronger transmitters and receiving antennas now allow higher direct current conversion, and ongoing tests are continually demonstrating rapid improvements in the technology. Recent ground experiments include one by the US Department of Defense's Naval Research Laboratory (NRL) in 2022, which marked the most significant power beaming demonstration in nearly 50 years: 1.6 kWof power over a distance of 1 km.[35]

Private sector company EMROD has developed a WPT system through which the combination of transmitters and receivers can achieve efficiencies of up to 95%,[36] and aerospace firm Airbus successfully proved the efficiency of its WPT technology in 2022.[37] One of the most critical advances, however, was made in 2023 when a team led by the California Institute of Technology (Caltech) achieved the first WPT from a prototype in orbit to a ground receiver, detecting solar power beamed down from a test satellite.[38]

In terms of scalable energy sources, SBSP is particularly attractive as it offers a domestic, renewable energy alternative that enhances **energy independence and resilience** in the face of disruptions and other geopolitical uncertainties. The United Kingdom's Space Energy Initiative (SEI) has stated that deploying SBSP could provide a large fraction of the country's electricity from space.[39]

Companies in **new technology- and innovation-driven industries** are also contributing to the gathering momentum around the need for scalable energy sources. Increasingly, new energy-intensive industries, such as data centres and hydrogen production, cannot rely on grid capacity for their energy needs. Many such companies are seeking longer-term solutions to support their energy demand and are already working with SBSP technology developers to determine future energy supply.

This momentum around SBSP technology, including government and private sector investment and initiatives, is resulting in an acceleration of technology development across the key components of SBSP. The commercialisation or technological readiness of these components will determine the rate at which ongoing demonstrations are converted into large gigawatt-scale commercial solar farms.

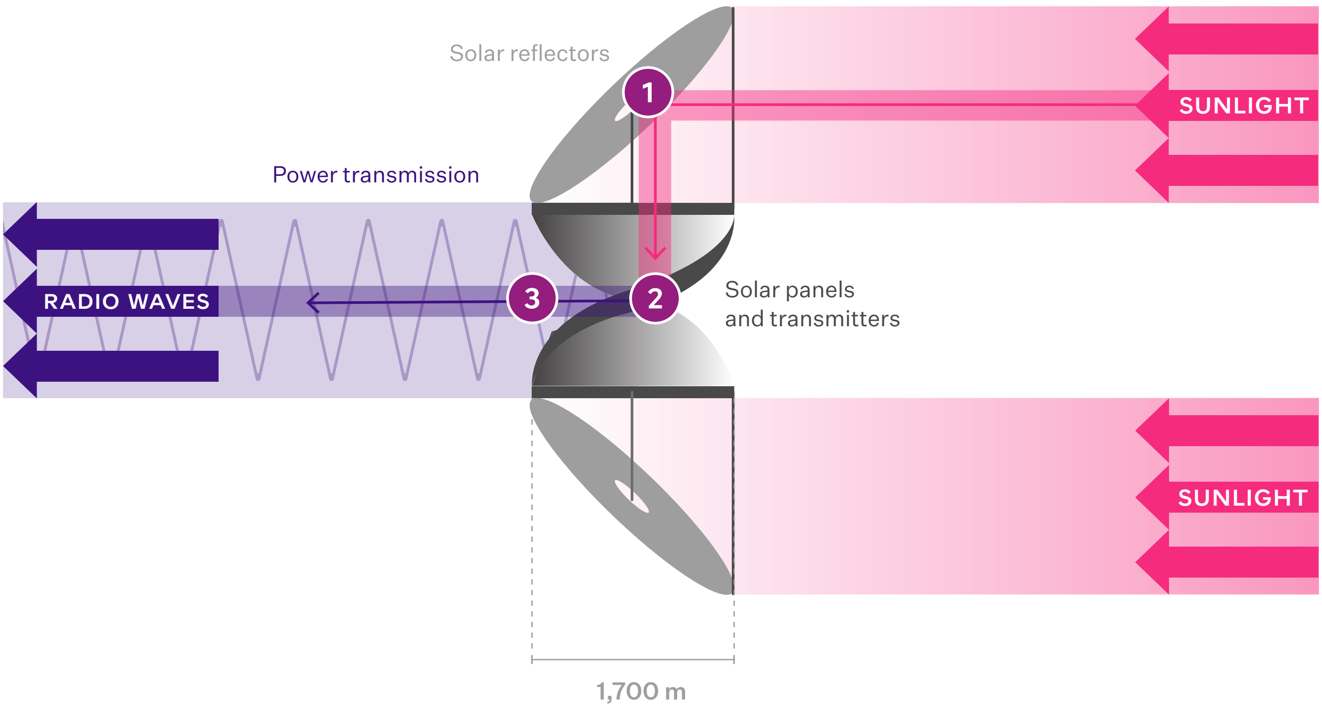
4

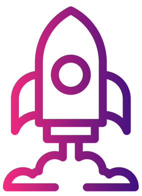
SPACE-BASED SOLAR POWER TECHNOLOGIES TODAY

As SBSP technology continues to develop, directly or as a spillover effect from other developments, it will be essential to understand both technological readiness and the international landscape in order to anticipate future scenarios. This section examines the current state of key SBSP components and the major international initiatives that are shaping the development trajectory of SBSP. SBSP essentially comprises five key advanced technologies: rocket launches, on-orbit assembly, solar cells, WPT, and ground receiving stations. For large-scale SBSP to be economically viable, i.e. cost-effective and efficient, the energy collected in space must be competitively priced compared with energy collected on Earth. It is important to note that parts of SBSP still need to reach complete technological readiness as they are not yet cost-effective and are presently used only in small-scale, specialist space applications.

As seen in Figure 1, space solar satellites consist of 1) solar reflectors designed to reflect sunlight onto solar panels; 2) solar panels and transmitters, whose primary function is to convert the reflected sunlight into high-frequency microwaves; and 3) a power transmission system, which transmits the microwaves to the ground receiving antennas. Five key technologies are required to deploy a satellite within the broader SBSP system.

Figure 1. Overview of CASSIOPeiA design





Launch technology

Launch technology and the cost of launches together form a critical component of SBSP as the deployment of an SBSP satellite will require multiple launches over time. Primarily to reduce the complexity of sending a single large, heavy satellite into space, the various components of the satellite will need to be transported separately, meaning that final deployment will require multiple launches. Over time, additional launches will be needed for satellite maintenance. Given that launch technology is already commercially viable and costs are continually declining as competition in the industry grows and the overall number of launches increases, experts interviewed for this report agreed that this component of SBSP is a low risk to commercialisation.

> **The growing number of space missions will require increasing energy solutions, driving the demand for mass production of solar cells and further improving their cost-effectiveness.**

On-orbit assembly

Advances in robotics and autonomous assembly are leading to the potential for solar arrays to be built in space without human crews. Given that the components of SBSP satellites will be transported into space separately, they will need to be assembled in space through the use of robotic 'on-orbit' assembly. Although robotic assembly is already being used in space missions, specific robotics technologies still need to be adapted for SBSP satellite construction. Ultimately they will need to be mass produced to achieve economies of scale and allow SBSP to become cost-effective. This component of SBSP requires significant development to reach full-scale commercialisation given the vast range of input robotics technologies that need to be manufactured.

Power generation

Existing space missions already use solar cells; for example, the International Space Station currently has eight main solar arrays.[40] Significant innovation and the improving cost-effectiveness of space-stable solar cells indicate that ongoing development will continue to strengthen the effectiveness of solar cells for SBSP applications. The experts interviewed agreed that this component of SBSP has already achieved commercialisation. Over time, the growing number of space missions will require increasing energy solutions, driving the demand for mass production of solar cells and further improving their cost-effectiveness.

Wireless power transfer

Solar power collected by SBSP satellites can be transmitted to Earth through either microwave or laser beams.[41] The experts noted that although the technology has been demonstrated, increasingly larger tests which improve its efficiency and range will help to bring WPT closer to commercialisation and application in SBSP. Examples include large space demonstrations in the next few years by Japan, China, Virtus Solis, Space Solar, and Airbus, among others.

Receiving ground stations

Energy transmitted from satellites will be received on Earth and converted into usable power via a 'rectenna' (rectifying antenna) or a ground-based receiving station consisting of antennas that convert the microwave beams into DC power.[42] The interviewed experts noted that although rectennas have been demonstrated in laboratory settings for years, and researchers have successfully designed and tested them to convert microwave and radio-frequency signals into electric power, further tests are needed to integrate rectennas with satellite and power transmission systems. Rectenna technology is, therefore, at a high readiness level, although it still needs to be integrated into broader SBSP systems to reach commercialisation.

BOX 5
Additional Innovative Solar Technologies and Designs (Non-exhaustive)

Several innovative solar technology concepts and designs, beyond conventional satellites, have been, or are being, explored.

- **Orbiting space reflectors:** These are large-scale structures in space that reflect concentrated sunlight to Earth to power solar panels for longer durations. To increase the amount of sunlight the panels receive, wide panels placed in orbit reflect additional sunlight towards ground-based solar farms, increasing the energy produced by approximately 15–20 minutes each pass and increasing the annual energy yield by up to 60% without modifying the ground structure.[43]

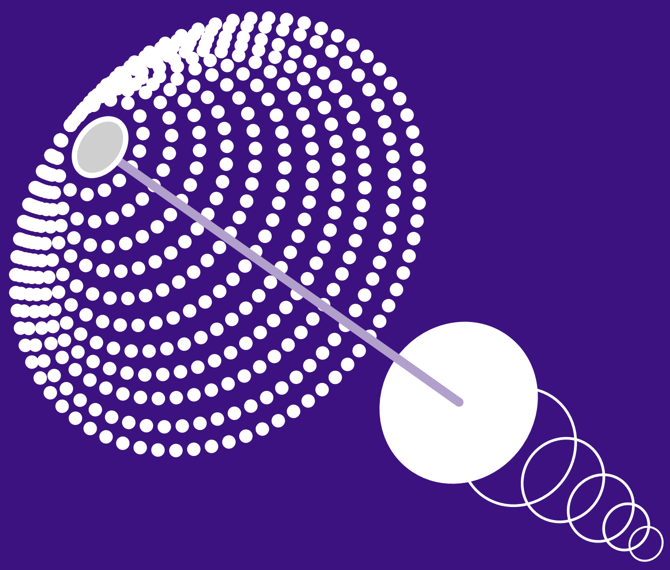
  While space reflectors could increase the yield of existing ground-based solar farms, they will not provide a truly scalable solution in comparison with SBSP technology.

- **Varied satellite designs:** Several different designs of SBSP system have been proposed over the years, such as the Solar Power Satellite via Arbitrarily Large PHased Array (SPS-ALPHA); the Constant Aperture, Solid-State, Integrated, Orbital Phased Array (CASSIOPeiA); and, more recently, the Korean Space Solar Power Satellite (K-SSPS).[44]

SPS-ALPHA

Solar Power Satellite via Arbitrarily Large PHased Array[45]

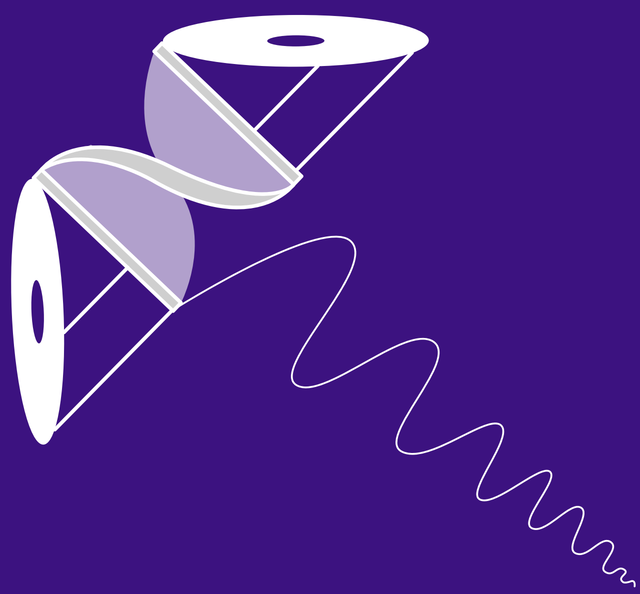
This is a leading design in SBSP by John Mankins. Numerous small modules of similar shape are assembled in space to form a large structure. These modules are thin-film mirrors used to convert sunlight into coherent microwave beams and transmit the energy created to rectennas on Earth. SPS-ALPHA encompasses a number of new technologies, such as a lightweight structural system, advanced solar cells that manage heat well, and WPT that uses an antenna to send energy back to Earth with high efficiency.



CASSIOPeiA

Constant Aperture, Solid-State, Integrated, Orbital Phased Array[46]

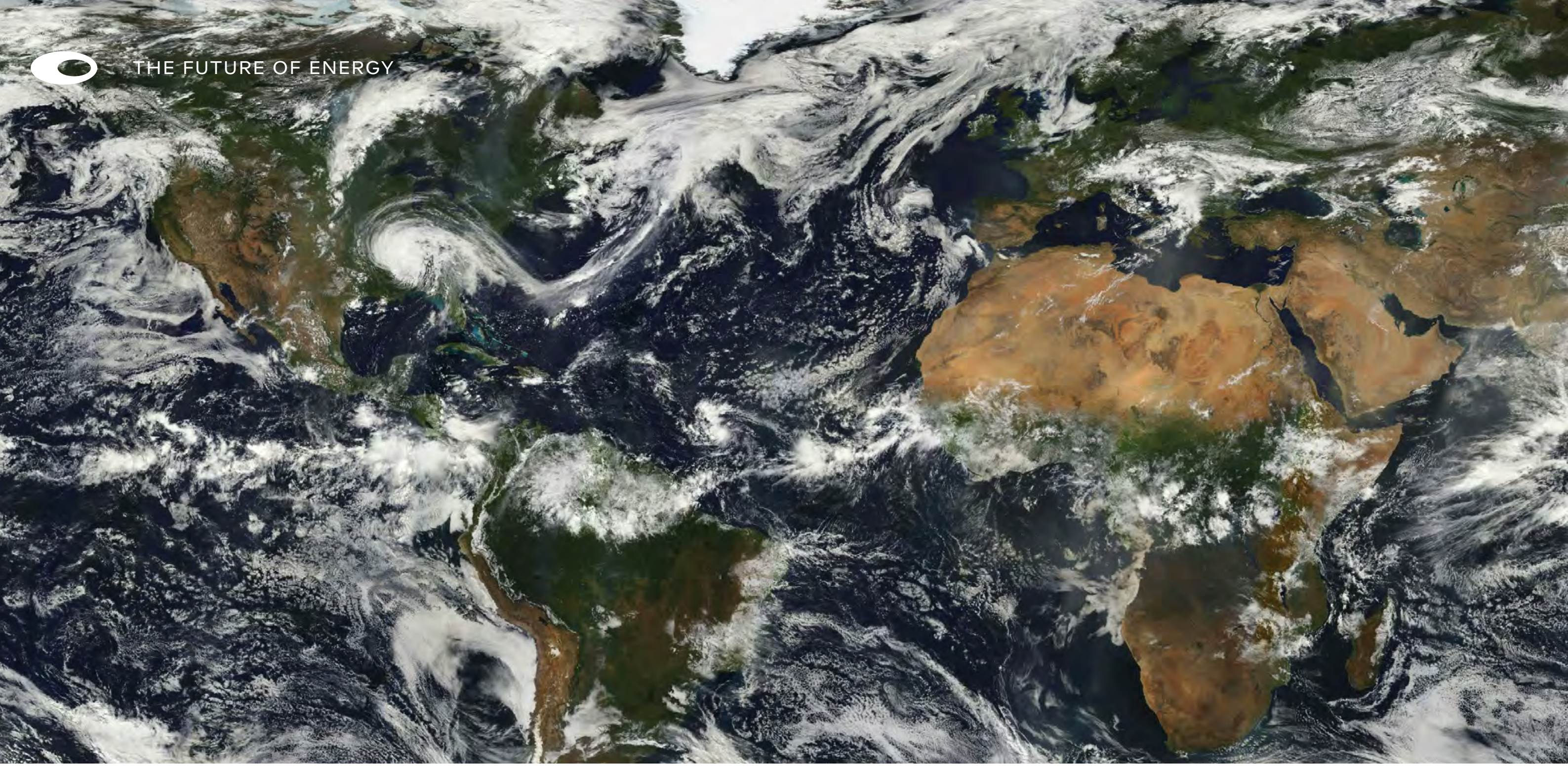
Designed by Ian Cash, Space Solar's chief architect, CASSIOPeiA uses wavelength-scale modular integration. Its unique design has no moving parts and constantly faces the sun without tilting. The structure is lightweight and compact and is designed to be unfolded when launched into space without extra support. Because there are no moving parts, the structure can be launched as a single payload and expanded in space to gain as much energy as possible.



All components of SBSP are either already commercialised or being adapted for commercial uses. Large-scale integrated demonstrations that prove the validity of an integrated SBSP system are the critical next step. Governments are launching these demonstrations to pave the way for multi-megawatt pilot plants in the next five to ten years.

5

THE INTERNATIONAL LANDSCAPE OF SPACE-BASED SOLAR POWER TODAY



A high proportion of technological demonstrations of SBSP are being carried out or funded by governments that have developed broader initiatives and road maps not only to further test and develop the technological system that makes up SBSP but also to develop a wider ecosystem that develops SBSP as a critical domestic industry across their space and energy sectors.

CHINA

China is emerging as a leading actor in SBSP development
The Chinese government and academia established a Committee on Space Solar Power (CSSP)[47] in 2021 and laid out a clear road map detailing the different phases of the CSSP's research. China is expected to complete phase 1 of its research in 2026–2028 by launching a kilowatt-scale demonstration into space. This will be followed by a megawatt-scale test in 2030 (phase 2) and a gigawatt-scale satellite in 2050 (phases 3 and 4).

Accordingly, Chinese researchers have already built the world's first integrated SBSP ground test facility, Zhuri.[48] At this site they have completed a full-chain ground verification of space solar power, including sunlight capture, conversion to microwaves, beam transmission, and reconversion at a receiver, and have tested key technologies, including high-efficiency concentrators, microwave transmitters, beam steering, and rectenna reception.[49] The system successfully transmitted energy over 55 metres and optimised beam control. The CSSP also conducts annual conferences to report progress, organises youth competitions calling for research on specified SBSP technology developments, and publishes a dedicated journal focused on SBSP research.[50]

Essentially, China's efforts are closely tied to its long-term energy strategy, which views SBSP as a way to enhance clean energy capacity. However, China is also pursuing international partnerships in SBSP and cooperating in international SBSP conferences. If China meets its interim goals (2026–2028 and 2030 demonstrations), it will achieve a leadership position which could spur other nations to speed up their programmes, potentially accelerating global efforts and leading to increased international investment in SBSP technologies.

EUROPEAN SPACE AGENCY

While China focuses on holding demonstrations by 2028, the ESA has established its own timeline and launched its comprehensive SBSP initiative, SOLARIS, in 2022 on the back of the Ukraine crisis, which accelerated government impetus to strengthen energy security and move away from fossil fuel imports. Simultaneous pressure to develop long-term climate strategies combined to bring energy security and the exploration of large-scale clean energy solutions to the forefront of government priorities.

Accordingly, in 2022, the ESA commissioned two independent cost–benefit studies on SBSP from consultancies Frazer-Nash and Roland Berger. These concluded that SBSP could provide competitively priced electricity to Europe's homes and businesses by 2040, displacing fossil fuels and complementing existing renewables, such as solar PVs and wind, and reducing the need for large-scale storage solutions. The studies found that when deployed at scale, SBSP would provide substantial environmental, economic, and strategic benefits for Europe, including energy security.[51]

The studies also noted that although considerable technological development is still needed to make it feasible to collect gigawatts of power in space, Europe has the main building blocks already and developments in the required technology areas will have widespread applications both on Earth and in space.

To this end, the ESA's space solar 'preparatory initiative', SOLARIS, seeks to establish the technical, political, and programmatic viability of SBSP for Europe. The ESA's road map outlines that research will be focused on the viability of developing a subscale demonstrator by 2030, a pilot space solar power plant by 2035, and a commercial-scale power plant by 2040. In line with the SOLARIS activity plan, the ESA has undertaken studies and technological development, in partnership with Europe's industry, to mature the technical feasibility and assess the benefits, implementation options, commercial opportunities, and risks of SBSP technology.[52]

JAPAN

Japan has been a pioneer in SBSP research for decades, with its earliest WPT tests conducted in 1983,[53] driven by its need for energy imports and its high technological prowess. The country has a coordinated road map involving government, academia, and industry which envisions commercialisation of SBSP by the 2040s. Over the years, Japan has achieved notable milestones, such as the 2015 demonstration of 1.8 kW microwave WPT with pinpoint control.[54] It has also tested robotic assembly techniques and laser-based power beaming on a smaller scale.[55]

A Japanese consortium led by Kyoto University and the Japan Aerospace Exploration Agency is working on a project called OHISAMA, which aims to perform a space-to-Earth power transmission test by 2025.[56] The plan involves a small satellite equipped with solar panels and a microwave emitter. The team has already demonstrated WPT on the ground and will test beaming from an aircraft to the ground over several kilometres.[57] This stepwise approach (ground to aircraft to orbit) is intended to incrementally prove the technology. If the 2025[b] orbital demonstration succeeds in beaming even a few watts or kilowatts to a ground station, it will be a world first for Japan (separate from Caltech's very-low-power test).

UNITED KINGDOM

The United Kingdom established the Space Energy Initiative (SEI) in 2022 to pursue space solar power after the country's Department for Business, Energy and Industrial Strategy published a study analysing the technical feasibility, cost, and long term economic viability of SBSP. The study concluded that space solar power is technically feasible and affordable and could bring substantial economic benefits to the United Kingdom.[58]

The SEI aims to establish the first orbital demonstrator SBSP system by 2030 and to deliver power to the grid by 2040. The first generation of solar power satellites (SPSs) would be in operation by the mid-2040s, replacing a substantial proportion of the United Kingdom's legacy fossil fuel energy generation capacity.[59] The SEI includes government, research, and industry players in the energy and space sectors.

[b] Based on the latest publicly available information available at time of publication

UNITED STATES

The United States has a long history of SBSP research but has only recently reignited large-scale efforts. NASA investigated the concept in the 1970s and again in the 1990s but a lack of economic viability prevented further exploration.

In recent times, various US agencies have embarked on SBSP research and development. In 2023, NASA's Office of Technology, Policy, and Strategy released a major report analysing SBSP's viability for 2050.[60] The US Department of Energy has also hosted workshops on space solar, linking it to broader energy strategy.[61]

The US Air Force Research Laboratory (AFRL) is investing in space solar beaming for military applications through its Space Solar Power Incremental Demonstrations and Research (SSPIDR). The rationale is to provide energy to remote bases where fuel delivery is difficult. The AFRL is launching a series of experiments, the key one of which is Arachne, a satellite that will test the conversion of solar energy into microwaves with a novel array and beam the microwaves to a receiving antenna. Arachne is scheduled for launch in 2025.[c] These defence-driven projects aim to validate SBSP on a small scale and improve component technologies (such as high-efficiency solar conversion and beam steering). If they are successful, the military could become an anchor customer for SBSP, accelerating development.[62]

[c] Based on the latest publicly available information available at time of publication

The US Department of Defense's Naval Research Laboratory (NRL) designed the world's first satellite powered by solar cells – Vanguard 1 – which was launched in 1958. Since then, the NRL has been involved in a variety of solar power research projects, including the following related to SPSs:

- **Photovoltaic Radio-frequency Antenna Module (PRAM):** The first orbital SPS experiment was launched on the sixth mission of the US Air Force's space plane, in May 2020. The space plane carried and tested a sandwich module developed by the NRL. It also featured a PV module to test the viability of SBSP systems by converting sunlight into microwaves and analysing the energy conversion process and resulting thermal performance.

- **LEctenna:** This light-emitting diode rectenna converted a wireless network signal into electric power in an experiment on the International Space Station in February 2020.

- **Power Transmitted Over Laser:** The NRL conducted a successful demonstration of a land-based power-beaming system using an infrared laser in 2019.

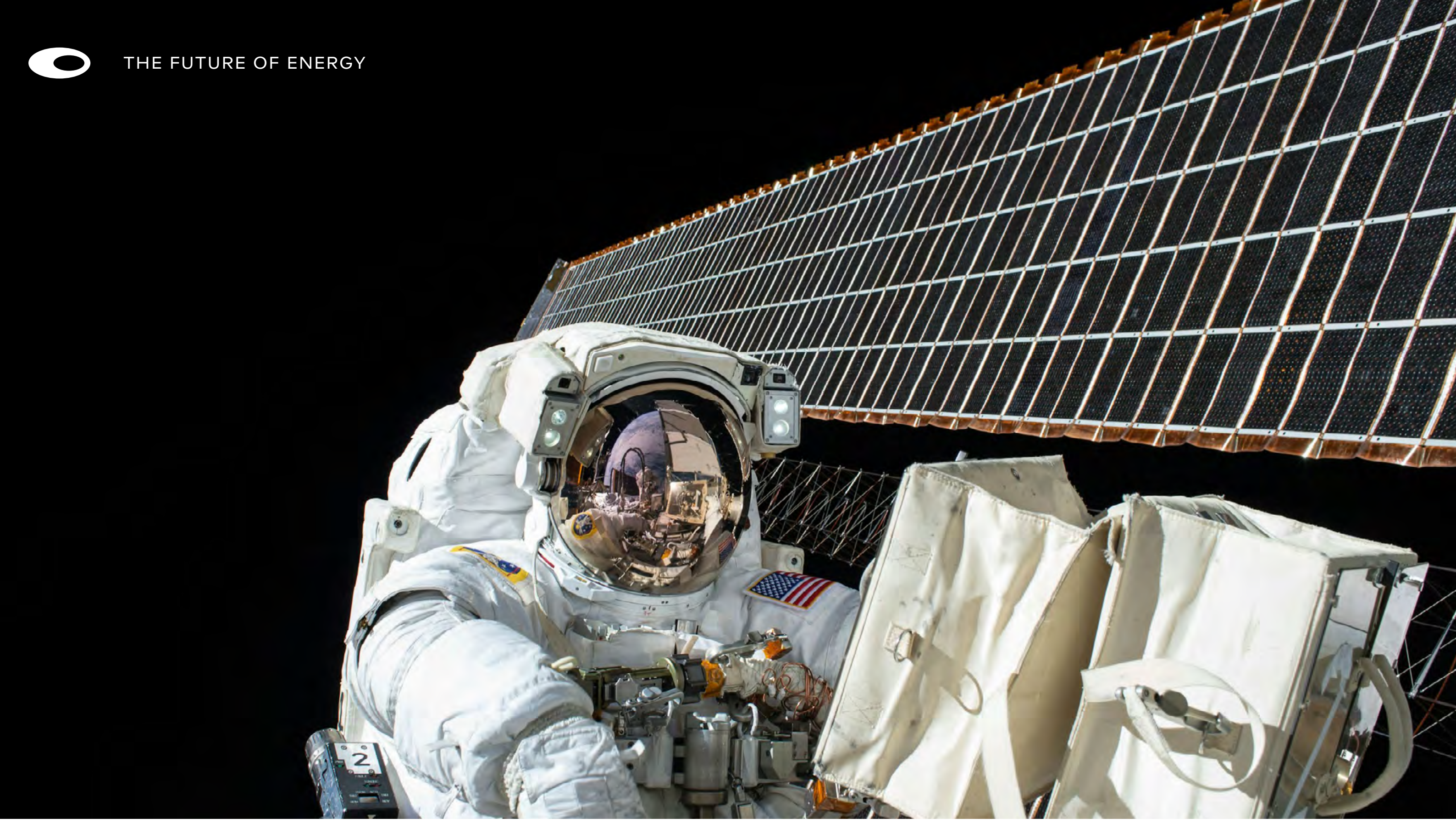
- **Microwave power beaming:** The NRL sent 1.6 kW over a distance of more than 1 km in 2021.

The various countries or blocs pursuing SBSP have comparable timelines, with the next five years expected to see the initial pilots and demonstrations and gigawatt-scale plants scheduled for the next 10–20 years. Although, so far, efforts are largely aligned with national and institutional priorities, going forward it is likely that increasing cooperation and coordination across different agencies will be needed.

> **"The various countries or blocs pursuing SBSP have comparable timelines, with the next five years expected to see the initial pilots and demonstrations and gigawatt-scale plants scheduled for the next 10–20 years.**

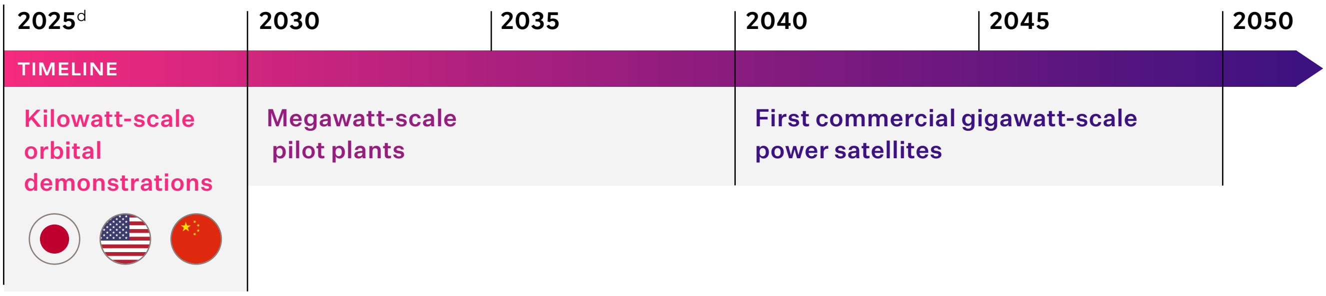
6

THE CRITICAL PATH TO COMMERCIALISATION OF SPACE-BASED SOLAR POWER



Based on our research, SBSP development will likely progress through three phases (see Figure 2): kilowatt-scale orbital demonstrations (Japan, United States, China) within five years (2025–2030), megawatt-scale pilot plants within 10 years (2030–2035), and the first commercial gigawatt-scale power satellites within 15–25 years (2040–2050).

Figure 2. SBSP development timeline



Source: DFF research

While no fundamental scientific breakthroughs are required to realise the commercial viability of SBSP, the path is challenged by complex engineering and logistical hurdles. Recent progress, such as the first power-beaming demonstration from space by Caltech in 2023, and falling launch costs have renewed optimism. Nevertheless, many of the experts we interviewed agreed that without transformative advances across multiple technological systems, SBSP will struggle to become more than a niche supplement to terrestrial renewables.

[d] Based on the latest publicly available information available at time of publication

1 LAUNCH AND ON-ORBIT ASSEMBLY REQUIREMENTS

Despite the falling cost of launches and the evolving reuse of rockets, transporting satellite components (or all components of SBSP more generally) is expected to remain expensive. The designs of most SBSP systems indicate that the structures will span hundreds of metres or several kilometres and weigh thousands of tonnes, making deployment challenging and costly. On-orbit assembly of such large structures is another critical challenge that is yet to be overcome. As human intervention during a geostationary orbit is not feasible, autonomous or robotic systems will need to become capable of precise, large-scale assembly and maintenance in space specifically of SBSP structures.

2 WIRELESS POWER TRANSFER SAFETY AND EFFICIENCY

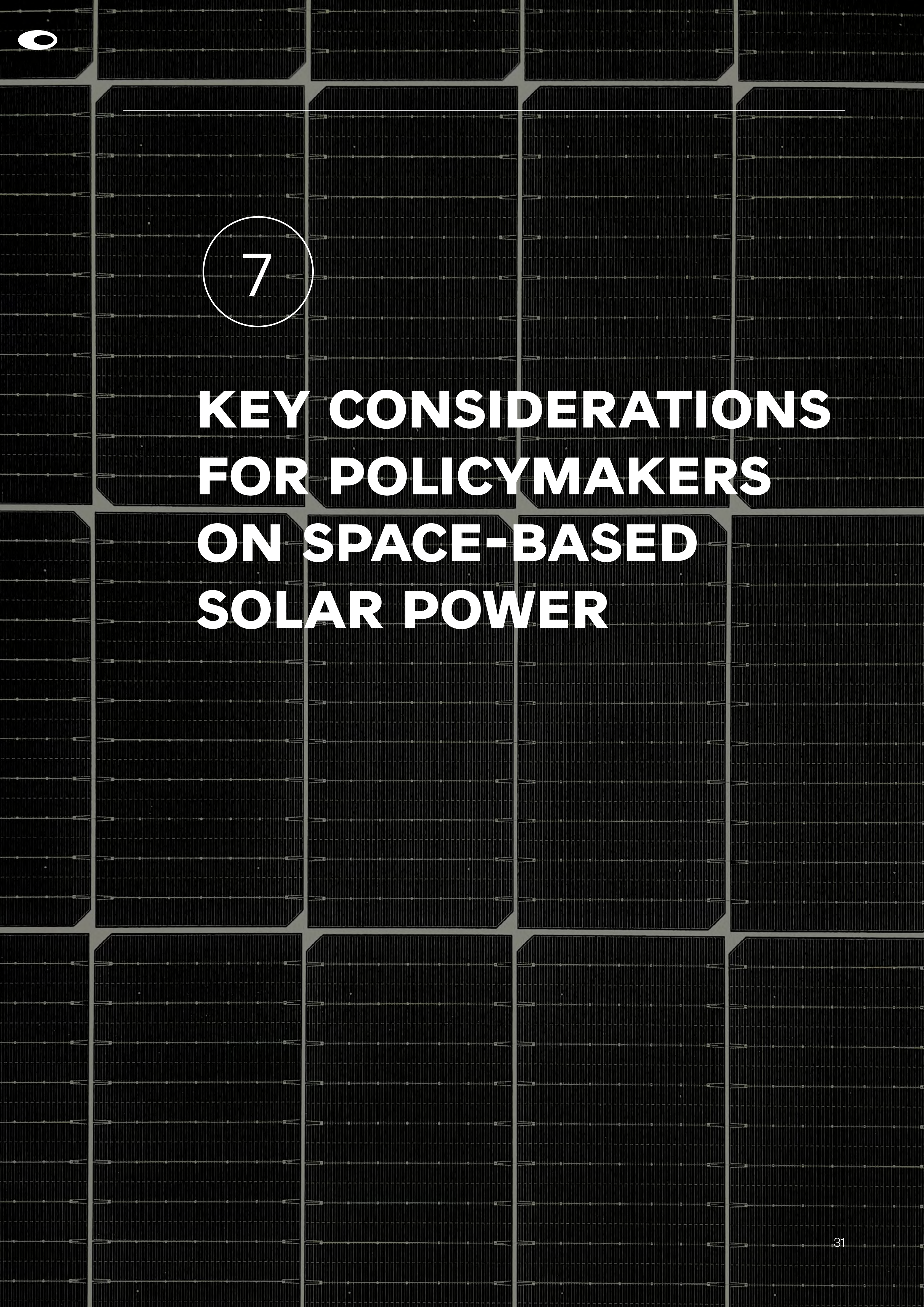
SBSP relies on converting solar power into microwaves or lasers, transmitting that energy over approximately 36,000 km, and then reconverting it into electricity on Earth, with notable energy losses occurring at each step. Microwave transmission (the preferred option) demands kilometre-scale antennas in space and on Earth, precise beam control, and high safety standards to avoid harming people or wildlife. Efficiency gains in radio frequency transmission and rectification are essential for SBSP to become economically competitive.

3 THERMAL MANAGEMENT IN SPACE

In orbit, waste heat from solar panels and transmission electronics is dissipated only through radiation, which adds to the excessive heat already produced in space. Excessive heat build-up can degrade solar panel performance and damage electronics. The experts interviewed agreed that balancing solar collection with heat rejection, without adding excessive mass or interfering with power beaming, is a complex engineering problem.

4 SPACE DEBRIS, COLLISION RISK, AND END-OF-LIFE DISPOSAL

Large satellites have increased risk of collision with space debris, especially in crowded orbits. Even small objects could damage critical SBSP components, resulting in a damaged SBSP satellite, which could become a major debris source itself. End-of-life deorbiting or disposal strategies for kilometre-scale structures remain undeveloped and will need coordinated international oversight.



7

KEY CONSIDERATIONS FOR POLICYMAKERS ON SPACE-BASED SOLAR POWER

For nations not yet engaged in SBSP development, two strategic factors will shape potential participation: **speed of technological maturity in SBSP components** and **level of international coordination on space and SBSP**.

As technological advances in SBSP components accelerate – driven by those countries that have already invested in this area – entry barriers will gradually fall. Cheaper launch costs, maturing wireless power systems, and scalable manufacturing could enable more countries to participate, even without leading programmes.

The global scale and orbital footprint of SBSP infrastructure will require unprecedented cooperation. Governance frameworks will be needed to address deployment, spectrum management, orbital slot sharing, power beam regulation, and environmental impact. Nations not yet involved still have an opportunity to help shape these frameworks.

As such, and besides monitoring the policy and technological developments in SBSP, countries assessing potential SBSP involvement could begin by evaluating alignment with their national energy and space strategies. If relevant, they can:

- consider looking into integrating SBSP-related technologies (e.g. robotics, WPT, rectennas) into existing research and development programmes and efforts
- build small-scale demonstration efforts and experiments to contribute to the related knowledge base and build domestic capability
- establish partnerships with nations already involved in SBSP and look at participating and engaging in joint workshops or hosting global dialogue on SBSP and related technologies and necessary enablers of future investment
- study the feasibility of building ground receiving stations should SBSP materialise in the future, and provisionally include SBSP infrastructure needs in future urban plans
- raise the awareness level of international coordination on space and SBSP.

$2 TRILLION

is the estimated SBSP market opportunity

The coming years will witness several proof-of-concept missions that will confirm how close we are to solving key challenges. Continued innovation in SBSP component technologies along with sustained funding commitments for full-scale demonstrations will likely narrow the gap between SBSP and other competing energy technologies, unlocking a forecasted $2 trillion market opportunity[63] and positioning SBSP as a major contributor to the future global energy mix.

CONCLUSION

The benefits and transformational impact of SBSP are undeniable. Constant clean power would be a game-changing scenario for most countries and would enable an entirely new economic and political reality. Recognising this, forward-looking governments and companies are developing SBSP technologies and focusing, beyond the incremental pace of progress, on longer-term gains and targets. Achieving the full promise of SBSP will depend on advancing key enabling technologies. While the long-term benefits are clear, overcoming current engineering and logistical hurdles is essential.

The advances made in any SBSP input technologies, whether WPT or robotic manufacturing, have countless applications across all industries on Earth and in space. The effort to develop these technologies can therefore only lead to a win-win scenario for all players. As is true with the timeless motivation for space science and research, solutions to technical challenges cannot always be reached with a direct approach. Many challenges require the motivation of higher goals and more extreme environments, demanding that engineers, scientists, and institutions develop solutions with greater precision. The constraints inherent in space applications necessarily strengthen the efficiency and accuracy of any technology, allowing it to surpass technologies developed solely for ground applications.

Given that energy is one of the most critical inputs to all economic growth, all viable energy solutions merit investigation. Assessing the potential value of SBSP via a simple per-kWh comparison cannot capture the economic value of continuous clean power that does not require storage or backup, as there is no clear picture of other potential competing sources that could offer comparable value.[64]

Nations might invest in SBSP for energy security or technological leadership, accepting a lower return on investment in purely financial terms in the initial years. For instance, being the first to develop space solar power could secure a country a strong position in what might become a critical energy industry in the latter half of the 21st century. Large-scale and long-term initiatives by countries such as China and Japan indicate both a strategic and an expansive motivation. Nevertheless, the involvement of private sector entities in exploring and investing in SBSP technologies is also an important trend to note; although state-led space programmes typically pursue research to support longer-term national objectives, investment from private sector entities is indicative of near-term commercial potential.

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Under the supervision and with the support of His Highness Sheikh Hamdan bin Mohammed bin Rashid Al Maktoum, Crown Prince of Dubai, Chairman of the Executive Council of Dubai, and Chairman of the Board of Trustees of the Dubai Future Foundation, the Dubai Future Foundation works on a three-pronged strategy: to imagine, design, and execute the future. It does this through the development and launch of national and global programmes and initiatives, preparing plans and strategies for the future, issuing foresight reports, and supporting innovative and qualitative projects. These contribute to positioning Dubai as a global capital for the development and adoption of the latest innovative solutions and practices to serve humanity.

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The Dubai Future Foundation oversees many pioneering projects and initiatives, such as the Museum of the Future, Area 2071, The Centre for the Fourth Industrial Revolution UAE, Dubai Future Accelerators, One Million Arab Coders, Dubai Future District, Dubai Future Solutions, Dubai Future Forum, and Dubai AI Week. Its many knowledge initiatives and future design centres contribute to building specialised local talents for future requirements and empowering them with the necessary skills to contribute to the sustainable development of Dubai.

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