Space Energy Initiative

Space Based Solar Power – answering questions

September 2021

Environmental

1. Will it heat up the world? Just what we're trying not to do…

Claim: No, initial assessment suggests it will have a very minimal heating effect.

Argument: All the energy we use ends up as heat in the environment. All renewable energy, be it from wind, solar, hydro or biomass, is ultimately derived from the incident solar radiation on the earth. The question is whether SBSP will add significantly to the energy received on earth and therefore lead to higher environmental temperatures.

- Initial assessments suggest that the additional energy supplied by SBSP is insignificant compared to the sun's power absorbed by the atmosphere and ground.
- Studies have indicated that the presence of large-scale wind farms and solar farms also have a potential to affect the climate.

The long-term interaction of these energy chains and their impact on the global climate is a complex problem that merits further investigation.

Evidence: The sun delivers approximately 113,000 TW into the earth's energy budget, absorbed in the atmosphere and on the earth's surface. The total world primary energy usage (to generate electricity, provide heat, drive transport and industry etc) is of the order of 19 TW. Assuming 10% of all the world's energy was derived from SBSP, this would only be an additional 0.002% addition to the earth's energy budget. To put that figure in context, the sun's output varies by about 0.1% over the course of a solar cycle

2. Will the radio frequency beam heat the atmosphere? This could be problematic

Claim: No, it won't heat up the atmosphere. There is minimal absorption of the radio frequency energy by the atmosphere at frequencies below 10 GHz.

Argument: Most systems use either 2.45 Ghz or 5.8 GHz. On a dry day there will be negligible absorption, and hence heating, by the atmosphere. On an overcast day with heavy precipitation, there may be up to 2% energy absorbed by the atmosphere. For safety considerations the maximum beam intensity will be limited to 245 W/m^2, thus the atmospheric heating will be less than 5 W/m^2.

Evidence: A study by Andrew Ross-Wilson, atmospheric scientist at Strathclyde University, calculates the local maximum temperature rise to be in the order of 0.006ºC due to this heating.

3. Scintillation in the ionosphere could be a problem

Problem: Could the radio frequency energy beam be disrupted by ionospheric scintillation, the radio analogue to the twinkling of starlight. ESA have had occasional but significant scintillation issues on satellite communications downlink in 2.1 to 2.3 GHz frequency range.

Claim: This is an area that would benefit from further study. Adaptive optics could mitigate this problem in the same way that they do for visible light astronomical telescopes.

Argument: The energy beam is controlled by a retrodirective pilot communications beam from the rectenna to the satellite. This could work in a similar way to adaptive optics in visible light telescopes – distortion of the pilot beam would be compensated by the phase conjugation (time-reversal) performed at the satellite. Of course, this depends on the ionospheric turbulence having a time constant longer than the lightspeed delays and the pilot/power beam frequencies to be similarly affected.

Evidence: This issue requires proper study as part of a development programme.

4. Will these massive satellites cause light pollution for astronomers?

Claim: This needs to be explored further. Some points of consideration are discussed below.

Argument: A satellite in a geostationary orbit would appear stationary in the sky to a ground observer but would track across the starfield as the Earth turns. The solar power satellite design intentionally maximises the collection of sunlight, rather than reflecting it to Earth.

Despite the large size of the solar power satellite, because of the high orbit its visual angle when viewed from earth is less than $^1/_5$ of the International Space Station (currently the largest satellite orbiting earth).

The capabilities needed for SBSP, including low-cost space access, could facilitate further space-based astronomy, or systems located on the RF-quiet far-side of the Moon.

Evidence: This would need to be studied properly.

5. What about RF pollution especially for Wi-Fi at 2.45 GHz?

Problem: Forming and steering a narrow RF beam, and avoiding unwanted side lobes may be feasible, but needs to be studied. The consequences of RF pollution on other satellites could be substantial. The failure case where some modules do not steer in the phase locked direction also needs to be examined, so these can be reliably switched off.

Claim: This needs to be explored further. Some points of consideration are discussed below.

Argument: The trend for RF communications is to move to ever-higher frequencies and wider bandwidths. SBSP requires just one-or two narrow spot frequencies for the whole world to use. These are below 10 GHz, at relatively low intensity (compared to radar, say), and well below the currently popular Ku and Ka bands and so are unlikely to cause problems for other well-designed equipment.

This is one argument to use a Geostationary Laplace Plane (GLP) or other orbit, distinct from the comms-satellites congesting Geostationary Earth Orbit (GEO). If proven necessary, an SPS could briefly pause power transmission as it crosses the GEO equatorial plane.

Rectennas are likely to be positioned well away from areas of human habitation.

Evidence: This requires proper study during the development programme and international agreement on frequency allocations.

6. Would the microwaves be harmful to wildlife and small birds?

Claim: The objective is to specify a maximum power density for the energy beam that is safe for the environment and wildlife. This is an area that needs to be explored further. Some points of consideration are discussed below.

Argument: Some studies (US Department of Agriculture, 2015) have been done on the effect of radar on bird life at airports, with some evidence that birds are aware of the electromagnetic radiation. Further research is needed to determine whether microwave radiation poses a hazard to birds flying through or exposed to the beam.

Evidence: This issue needs proper study during the development programme and international agreement on safe power levels.

7. Space launch releases so much carbon into the atmosphere that SBSP will only make matters worse, not better

Claim: Space launch can use electro-synthesised “green” carbon-based (e.g. CH_4) or carbon-free (e.g. H_2) propellants.

Argument: An analysis for CASSIOPeiA based on the Reaction Engines SBSP paper, with fully reusable launch to LEO (and subsequent lift to MEO with a reusable space tug for assembly, before self-propulsion out to GEO) determines an energy payback period of 23 days for electrolysis and liquefaction of all needed hydrogen propellant.

Evidence: Ian Cash, ISDC 2018 presentation. This issue requires a proper study as part of the development programme.

Societal / safety perception

8. Can it be used as a death ray / beam weapon?

Claim: No, the system by design cannot be used as or converted into a weapon.

Argument: The aperture size of transmitter and receiving antenna are sized to keep the maximum beam intensity at or below 245 W/m^2. This is only one quarter of the intensity of sunlight at noon, which is around 1,000 W/m^2.

Lacking a common power bus, it would not be possible to re-purpose the power distributed across the platform to power a separate laser or particle weapon.

Evidence: This issue of weaponization should be clarified during the development programme to address societal concerns.

9. What if the microwave beam strayed over a populated area?

Claim: The system will be designed so that it is safe in the event that humans or birds or animals strayed into the beam.

Argument: The aperture size of transmitter and receiving antenna are sized to keep the maximum beam intensity at or below 245 W/m^2.

The SPS requires co-operation from a secured and encrypted pilot beam at the intended rectenna target to form and steer the power beam to itself. Without it, the power beam would immediately cut off. Even if RF continued to be generated, it would disperse omnidirectionally, with very low intensity at Earth's surface.

Evidence: Safety is a key requirement, which needs to be considered as an integral part of the development programme.

10. Would the microwave be hazardous / disruptive to aircraft or spacecraft?

Claim: Any likely risk is to communications and navigation equipment. The compatibility of aircraft and spacecraft to the microwave beam would need to be studied. Further consideration is discussed below.

Argument: The trend for RF communications is to move to ever-higher frequencies and wider bandwidths. SBSP requires just one-or two narrow spot frequencies for the whole world to use. These are below 10 GHz, at relatively low intensity (compared to radar, say), and well below the currently popular Ku and Ka bands – so are unlikely to cause problems for other well-designed equipment.

Evidence: This issue needs to be studied during the development programme.

11. Can it cause 'Havana syndrome' – adverse medical symptoms?

Problem: In August 2017, reports began surfacing that American and Canadian diplomatic personnel in Cuba had experienced unusual, unexplained health problems dating back to late 2016. The number of American citizens experiencing symptoms was 26 as of June 2018. There was suspicion that the Cubans were using some kind of pulsed microwave weapon.

Claim: SBSP will use continuous (not pulsed) wave beaming, at peak intensities less than emitted by a mobile phone held to an ear.

Argument: Intense, pulsed microwaves can cause non-linear effects in media which could exhibit audibly. Cellular GSM telephones (deemed safe for public use) produce pulsed microwaves, which can be detected as audible interference in other equipment.

MRI scanners use intense, pulse microwaves and are deemed safe for routine medical use.

Evidence: This issue needs proper study, but there is empirical evidence to suggest that this is unlikely to be a problem.

Economic

12. Why hasn't this been done before?

Claim: Historically it has always been seen as too expensive, but recent developments in low cost launch, maturing technology and more modular SPS concepts are changing the economics. The global imperative to decarbonise economies is also prompting nations to invest in clean energy technologies.

Argument: The physics of diffraction and atmospheric absorption makes SBSP very difficult to scale-down economically below gigawatts of delivered power. This includes any pilot system delivering useful power.

A number of factors have encouraged a resurgence of interest in the concept, including:

- The cost of space launch reduced by 90% from \$20,000/kg to under \$2,000/kg, with that trend set to continue.
- Advances in semiconductor technology leading to improving efficiency for space use.
- New modular Solar Power Satellite designs (SPS Alpha, CASSIOPeiA) are much lower in mass and production cost.
- Increased concern about climate change has led to a renewed imperative by governments to study all clean energy technologies

Evidence: NSS-JOURNAL New Developments in Space Solar Power - Dec 2017. John C. Mankins.

13. What's the point of SBSP when terrestrial solar and wind is so cheap?

Claim: SBSP can provide continuous base load and dispatchable power, day and night all year round, irrespective of the weather. It thus overcomes the intermittency of terrestrial renewables. SBSP could offer competitively priced baseload energy. Baseload energy generation is essential for grid stability.

Argument: A Solar Power Satellite in GEO can see the sun for well over 99% of the time. It is only in the earth's shadow for a few hours each year around the spring and autumn equinox. Using a suitable microwave frequency such as 2.45GHz, the transmitted energy can be beamed through the atmosphere with negligible loss, even through clouds and rain.

Existing studies of SBSP economics claim that the Levelised Cost of Electricity could be around £50/MWh, which is competitive with intermittent renewables, and considerably less than nuclear power.

Intermittent terrestrial renewables place an additional burden on the grid to ensure security of supply. Analysis carried out for the Climate Change Committee estimated the cost of these measures to be £10/MWh to £25/MWh for generation mixes with 50% to 65% of variable renewables, rising to £25 to £30/MWh for a system with 75% to 90% of variable renewables.

Evidence: Frazer-Nash Consultancy Phase 2 report reference FNC 004456-51624R Issue 1.1, April 2021. Climate Change Committee, The Sixth Carbon Budget, Electricity Generation Report.

14. Don't all the conversion efficiencies and losses mean that SBSP is totally impractical?

Claim: No, it doesn't, and efficiency is not the only measure of practicality.

Argument: Because the energy source (the sun) is limitless and free, the efficiency only matters because it affects the size, mass and cost of hardware. There are losses in energy conversion down the energy chain through the Collect, Convert, Transmit and Receive elements. This governs the size of the Solar Power Satellite, and hence it's production and deployment cost, but not the practicality of operation of the system.

- Concentrating mirrors (94%)
- Primary and secondary optics (85%)
- Concentrated Photovoltaics (39.4%)
- DC to RF conversion on the SPS (85%)

- Atmospheric loss (0% to 2%)
- Airy disk beam capture by the rectenna (90%)
- RF to DC conversion at rectenna (85%)
- DC to AC conversion to the electricity grid (90%)

Overall efficiency from sunlight to AC power into the grid is therefore a notional 18%. Accounting for these factors, cost modelling analysis by Frazer-Nash shows that the LCOE (levelized cost of electricity, used to compare different methods of electricity generation on a consistent basis) falls between £37 and £74/MWh, which is competitive with terrestrial renewable technologies.

The utilisation (another broader measure of 'efficiency') of SBSP is nearly 100%, delivering power day and night year-round, compared to an average of 11% for terrestrial solar farms and 47% for offshore wind farms in the UK. Moreover, SBSP delivers baseload power, improving grid stability and reducing the need for other energy balancing systems on the grid.

For a given area of land or sea, SBSP produces 2.4 times more annual mean power than terrestrial solar farms and 12 times more than offshore wind farms.

Evidence: Frazer-Nash Consultancy Phase 2 report reference FNC 004456-51624R Issue 1.1, April 2021; Ian Cash ISDC presentation 2018; energynumbers.info

15. The economics depend on SpaceX launch – that's not a resilient solution

Claim: A SPSP programme will provide the market demand for development of a vibrant competitive reusable launch market.

Argument: Any Space Solar Power programme, national or more likely international, needs very substantial low cost – and hence fully reusable - space lift requirements, in the order of many times the current global launch capacity. SpaceX has led the way in reusable launch, and it is likely that this will spur competition from other providers. A SBSP programme will provide the market demand signal for these capabilities to be developed, though it may also need government support to develop the underpinning technology for reusable spaceplanes.

Evidence: Already there are two fully reusable heavy lift launchers in development – SpaceX Starship and Blue Origin New Glenn. RocketLab has announced the development of the Neuron fully reusable launch vehicle. Reaction Engines is developing the SABRE airbreathing engine which is designed for a future reusable single or two stage to orbit spaceplane. This is in the absence of a declared SBSP programme, and these efforts would only accelerate if SBSP were pursued with a substantial and well funded programme.

Resilience, Security and Defence

16. Isn't it vulnerable to attack by an adversary?

Concern: The very large satellites, part of our Critical National Infrastructure, may be vulnerable to attack by an aggressor nation, either targeting them through EMP (Electro Magnetic Pulse), or kinetic kill, or blast weapons.

Claim: The SPS is highly resilient, having no single points of failure and being highly modular it would be difficult to degrade by a kinetic projectile.

Argument: Weaponisation of space is prohibited by International Treaty.

The SBSP and its retrodirective beam steering would be protected by secure encrypted protocols to prevent disruption or theft of the energy by an adversary.

An adversary could attempt to disable the SPS through a kinetic energy collision, perhaps with an anti-satellite weapon. However the very large sparse structure would suffer local damage and being modular, would continue operating with only minor degradation.

The SPS modules are hardened against the harsh Space weather environment, so an EMP weapon (presumably thermo-nuclear) large enough to destroy the whole (kilometre scale) SPS would be a very severe escalation of hostilities. This is no different to the threat posed to terrestrial CNI infrastructure.

Evidence: This requires further study and careful consideration of the risks, resilience and countermeasures.

17. What about space debris?

Claim: The choice of operational orbits can reduce the risk of space debris damage. The satellite architecture is highly resilient to damage from space debris or micrometeorites.

But space debris is still a risk and both the operational orbits and the orbit raising strategy need study.

Argument: One operational architecture is for the satellites to be assembled in a Medium Earth Orbit, just above the inner Van Allen belt and with reduced space debris risk. CASSIOPeiA proposes the use of a Geosynchronous Laplace Plane orbit, which is free from congestion and with potentially lower space debris risk. Additionally it can use Highly Elliptical Orbits, which could be chosen to minimise the risk of space debris.

The very large, sparse, highly modular architecture means that there are no single points of failure, and should damage be sustained from space debris or micrometeorites, the satellite would continue to function minimal performance degradation. Repair or replacement of modules would be designed into the operational concept.

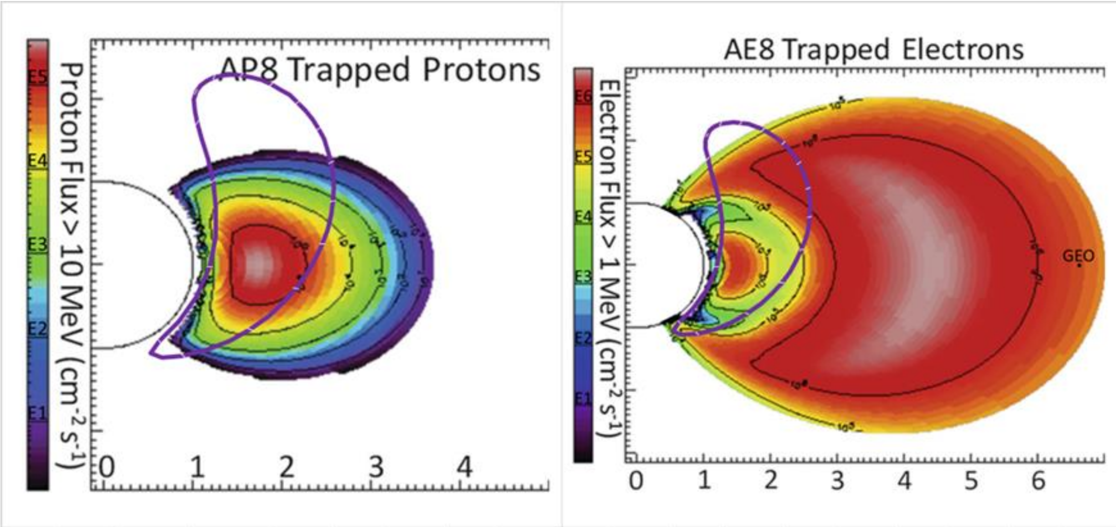
Evidence: Both SPS-Alpha and CASSIOPeiA have been designed with resilience as a key requirement, and this is achieved by the highly modular architecture. This issue needs careful study and optimisation as part of the development programme.

18. How does the SPS survive transit through the Van Allen belts?

Claim: It may be possible to design the launch trajectory to largely avoid the Van Allen belts.

Argument: The operational concept should be to avoid transit through the Van Allen Belts, and instead transit around it using an inclined elliptical transfer orbit to MEO assembly orbit. GEO is arguably still within the outer VA belt (see below). The images show an inclined, 4-hour period, highly elliptical operational orbit (compressed into a single vertical plane bisecting Earth's poles), avoiding both VA belts.

Evidence: This issue needs proper study as part of the development programme.



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