THE ECONOMICS OF SPACE BASED SOLAR POWER AND ITS RELEVANCE TO CLIMATE CHANGE

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ABSTRACT

The energy sector contributes 73.2% to carbon dioxide emissions and is highly dependent on fossil fuels without a sustainable alternative that could be supplied globally (Ritchie, 2020). Current renewable energy alternatives are highly variable depending on location. Space based solar power is a technologically feasible alternative to both of these problems. This article looks at the economic feasibility of this technology.

INTRODUCTION

Earth is currently facing both an energy crisis and an environmental crisis. Experts predict that within the next generation all known alternative energy sources on Earth will fall far short of projected need - including fossil fuels (Flournoy, 2012). In addition, continued carbon dioxide emissions at the current rate will increase the global temperature above the limit of 1.5-2°C set at the Paris agreement in 2015 (Carbon Tracker Initiative, 2021). The energy industry emits 73.2% of CO_2 (with electricity, heat and other energy uses contributing to approximately 35% of total emissions) and is the largest contributor to greenhouse gas emissions – see figure 1 (Ritchie, 2020; United Nations 2021). As the global temperature continues to increase, weather patterns will become more intense, unpredictable and disruptive. This means that renewable energy such as wind, solar and hydropower will not be reliable in offering base load power generation as the power output from them will become increasingly more volatile. Due to increased cloud cover due to rising ocean temperatures, there would be less sunlight for efficient terrestrial solar power generation as well (LBST Consortium, 2005). A potential sustainable renewable energy alternative to both aforementioned crises is space based solar power.

Space based solar power (SBSP) is the concept of collecting solar power in outer space and distributing it to Earth, the collection is done through a solar power satellite and energy is distributed via microwaves to a ground antenna (rectenna) which will be connected to the electrical grid (Flournoy, 2012). The SBPS system has three parts: the space system which has the satellite, solar array and the antenna; the ground system which has the rectenna that collects the microwaves and converts it to electricity and the launch system (LBST Consortium, 2005). The reason the launch system is included within the overall system is that the launch costs are a key variable to determine the costs of SBPS (LBST Consortium, 2005). The idea of SBPS has been around since 1941 when Isaac Asimov first published the science fiction short story "Reason". In 1968, aerospace engineer Dr Peter Glaser introduced the concept of a solar power satellite system, patenting the invention (Flournoy, 2012). Since then, NASA conducted the 'fresh look' study in 1997 that detailed the technical details and the economic costs for such a system, concluding that it was technically feasible but economically unfeasible at that time. Despite this, their recommendation was that the technology should be pursued (Mankins, 1997). From 2010 to 2016 there were several studies conducted by the US, China, Japan and the EU analysing the economic feasibility and the costs of implementing SBSP technology (LBST Consortium, 2005). From 2019 onwards, plans were announced by China, US and Japan to launch satellites in the 2030s (LBST Consortium, 2005).

SBSP is a sustainable renewable energy alternative for supply of base load power to the electricity grid because solar power in space is available constantly at a rate of 1367W/m² with the exception of predictable eclipse sequences where power generation will not occur (Nazir, 2018). However, the conversation surrounding solar powered satellites as a viable alternative has remained within a small group of private individuals, with entrepreneur Elon Musk being the most notable contributor. Currently, Musk has a space launch, solar power and a battery company, however he has yet to pursue SBSP in a meaningful way. He has also spoken about issues relating to converting sunlight to energy, suggesting that the solar powered satellites remain economically unviable for now (Doyle, 2012).

This article widens the discussion about the viability of SBSP by outlining and explaining the key factors that contribute towards deciding whether space based solar power is a viable alternative to established methods of producing electricity in order to fuel a more constructive debate with a wider group of stakeholders and suggests why it is an alternative that could be worth considering. The article offers an overview of the climate crisis and a background on SBSP. It continues with an explanation of the current climate related goals of world leaders and provides a timeline for SBSP development and operation within that timeframe. The levelised cost of electricity (LCOE), the energy conversion efficiency and power densities will then be addressed to determine the validity of the claims of conversion inefficiencies and transmission losses when converting sunlight to electricity and transmitting it down to earth, a detailed cost breakdown of the space and ground segments will be shown to assess how investment will be allocated in research and development and finally a risk assessment of microwave transmission to determine the safety standards required. Finally, it will conclude with an overall evaluation of the system and the implications of this for the global emission reduction target.

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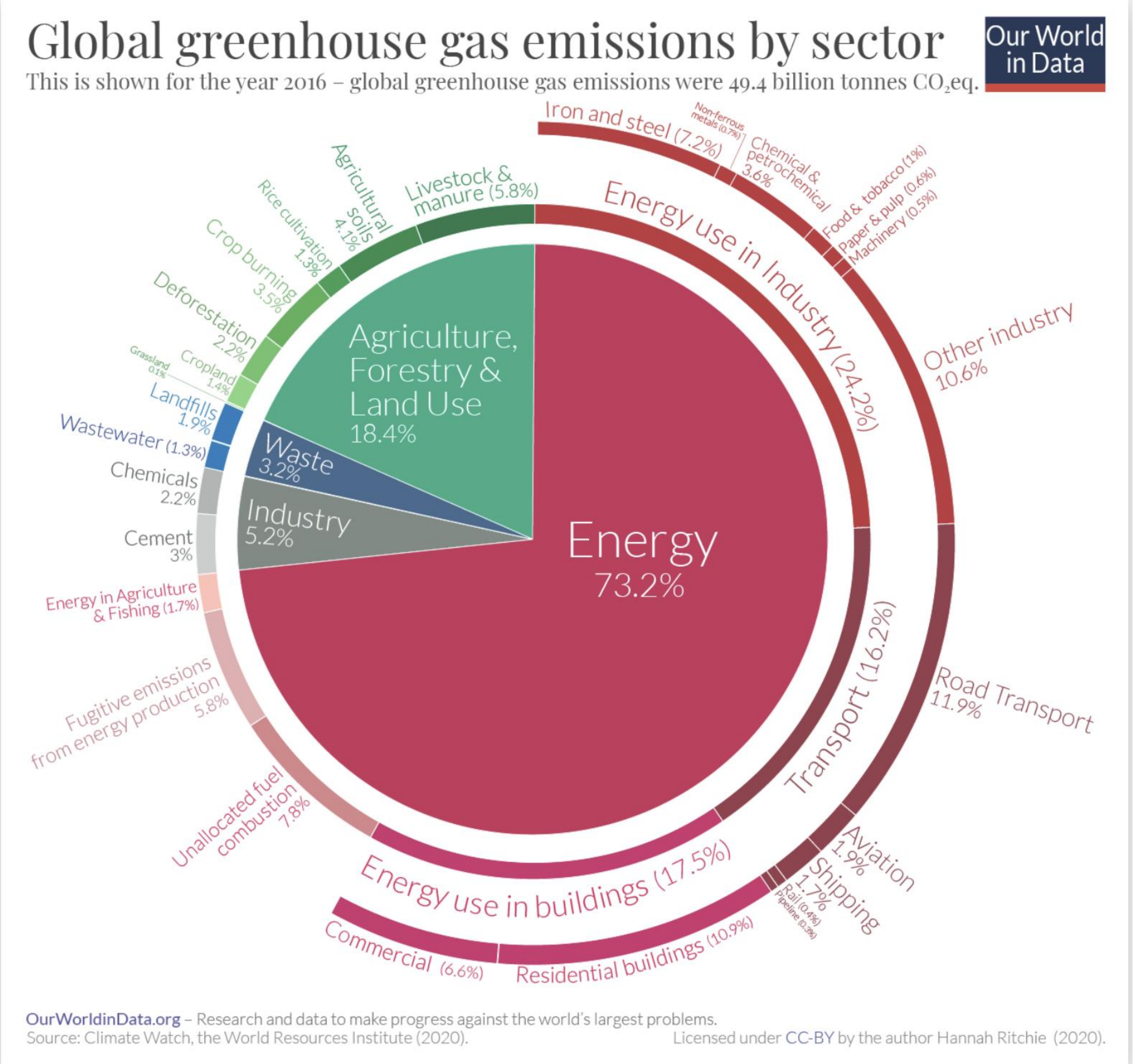
Figure 1. CO_2 emissions by sector (Ritchie, 2020)



Global greenhouse gas emissions by sector

This is shown for the year 2016 – global greenhouse gas emissions were 49.4 billion tonnes CO_2eq.

OurWorldinData.org – Research and data to make progress against the world's largest problems.
Source: Climate Watch, the World Resources Institute (2020). Licensed under CC-BY by the author Hannah Ritchie (2020).

SBSP DEVELOPMENT TIMELINE, COST ANALYSIS AND RISK ASSESSMENT

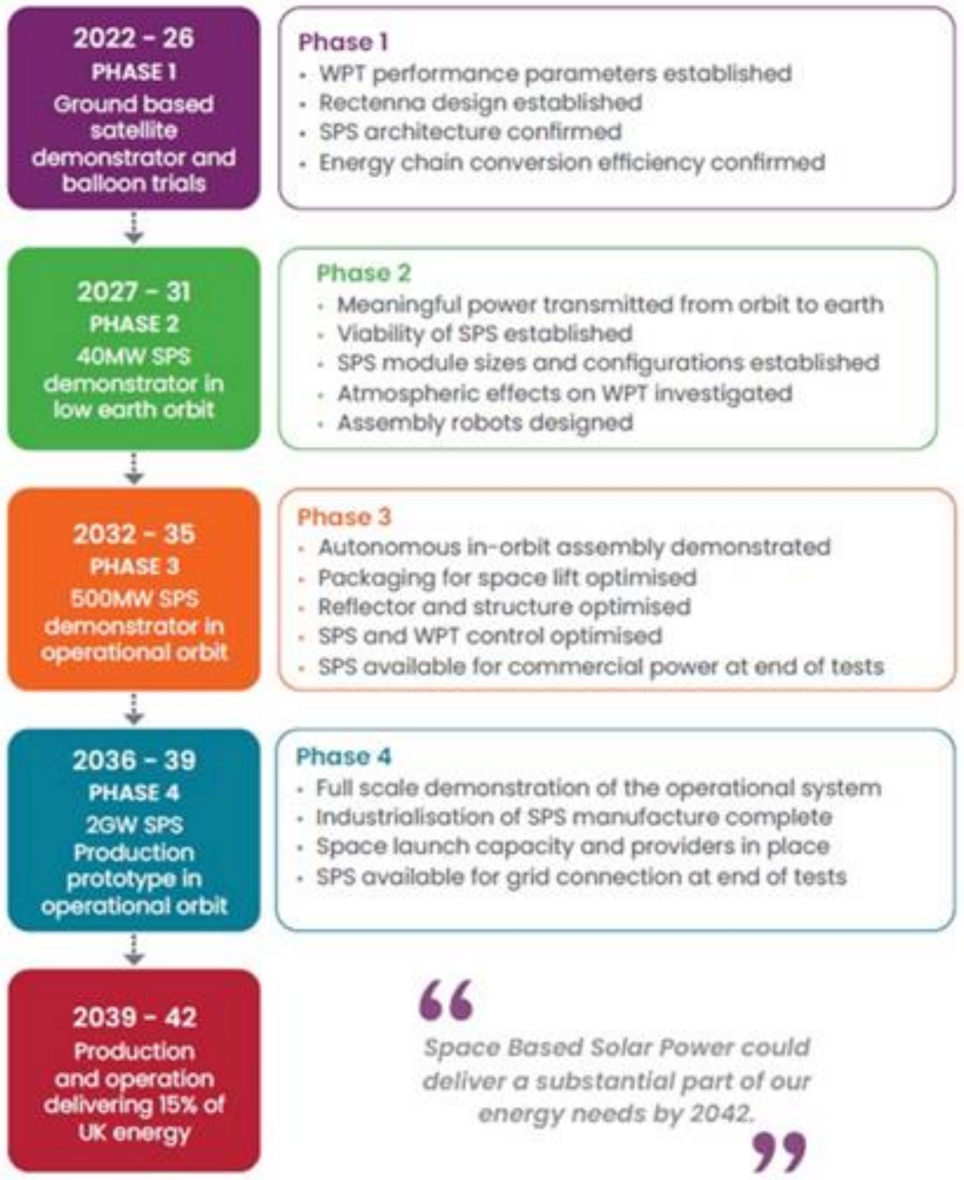
Development timeline

The current global target for emission reduction is net zero by 2050 (Frazer-Nash Consultancy Ltd, 2021). With the energy industry highly dependent on fossil fuels right now, it may seem like an ambitious plan. However, in September 2021, Frazer-Nash consultancy published a report that suggested a path to integrate SBSP technology to supply 15% of the UK power grid which is outlined in figure 2 (Frazer-Nash Consultancy Ltd, 2021).

Their findings indicated that SPSP offers a new source of economically competitive base load electricity but that public funding would be required for the majority of the development, given the substantial risk, cost and timescales. The estimated cost of development is £16.3 billion with an additional £1 billion operating expenditure over the lifetime of the system (Frazer-Nash Consultancy Ltd, 2021). Their analysis suggested that the public sector would need to fully fund phase one of the development (the establishment of a ground based satellite demonstrator and balloon trials) which would total £350 million (Frazer-Nash Consultancy Ltd, 2021). The distribution of public and private funding for the various phases is outlined in figure 3.

The competitiveness of an electricity generation system is determined by the levelized cost of electricity (LCOE) which is the average cost per MWh of building and operating a generating plant over an assumed financial life and duty cycle (Eia gov, 2021) The LCOE for SBSP calculated by the Frazer-Nash consultancy includes the end to end production, launch, assembly, operational service life and decommissioning of the system with an investment hurdle rate of 20%, and assuming the system is commissioned in 2040 (Frazer-Nash Consultancy Ltd, 2021). With these assumptions, the cost comes to £50 per MWh (Frazer-Nash Consultancy Ltd, 2021). The investment hurdle rate is the minimum rate of return or investment required for a project, it showcases the level of risk of a project (Kenton, 2021). This is a very high investment hurdle rate but was chosen to reflect the present low maturity of Space Based Solar Power (Frazer-Nash Consultancy Ltd, 2021). However, as the technology matures, a lower hurdle rate could be applied, thus

Figure 2. Timeline for SBSP development (Frazer-Nash Consultancy Ltd, 2021)



2022 - 26
PHASE 1
Ground based satellite demonstrator and balloon trials

Phase 1
- WPT performance parameters established
- Rectenna design established
- SPS architecture confirmed
- Energy chain conversion efficiency confirmed

2027 - 31
PHASE 2
40MW SPS demonstrator in low earth orbit

Phase 2
- Meaningful power transmitted from orbit to earth
- Viability of SPS established
- SPS module sizes and configurations established
- Atmospheric effects on WPT investigated
- Assembly robots designed

2032 - 35
PHASE 3
500MW SPS demonstrator in operational orbit

Phase 3
- Autonomous in-orbit assembly demonstrated
- Packaging for space lift optimised
- Reflector and structure optimised
- SPS and WPT control optimised
- SPS available for commercial power at end of tests

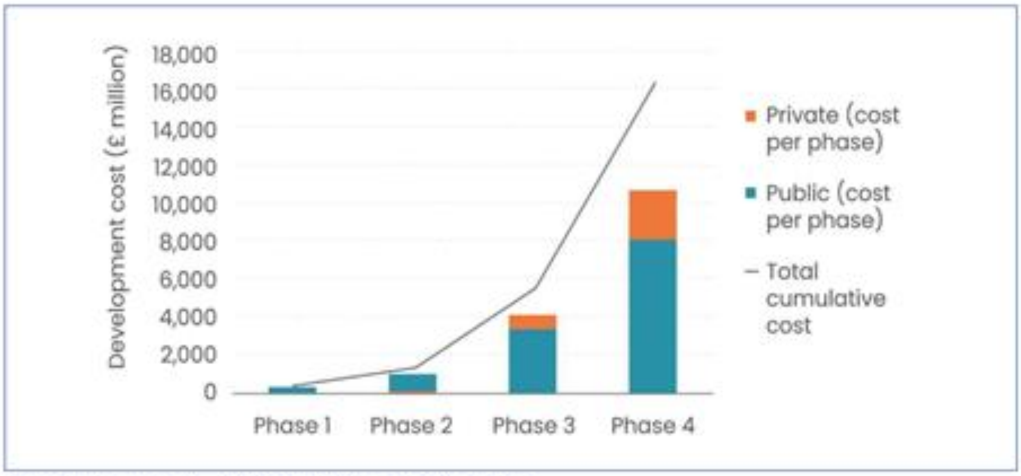
2036 - 39
PHASE 4
2GW SPS Production prototype in operational orbit

Phase 4
- Full scale demonstration of the operational system
- Industrialisation of SPS manufacture complete
- Space launch capacity and providers in place
- SPS available for grid connection at end of tests

2039 - 42
Production and operation delivering 15% of UK energy

“*Space Based Solar Power could deliver a substantial part of our energy needs by 2042.*”

Figure 3: Development costs and investment divisions (Frazer-Nash Consultancy Ltd, 2021)

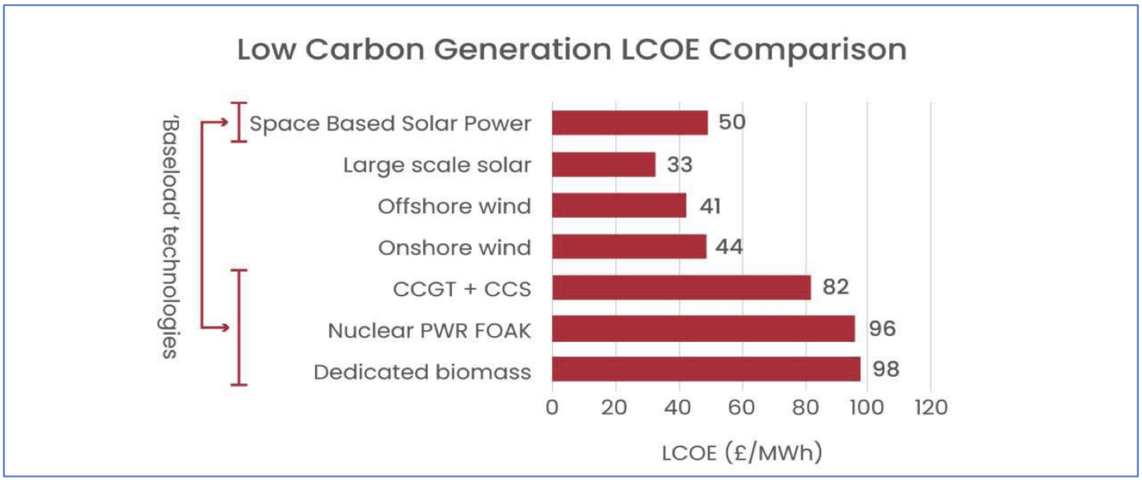


Development cost - NPV, including optimism bias

reducing the LCOE. As figure 4 below outlines, SBSP has a much larger LCOE as compared to the other renewables. However, when comparing it to other potential technologies that could offer base load power, it is the lowest, being comparable to onshore wind. Terrestrial solar power and offshore wind will not be able to offer base load power as they are volatile sources of energy, subject to constant changes based on weather patterns, location and time.

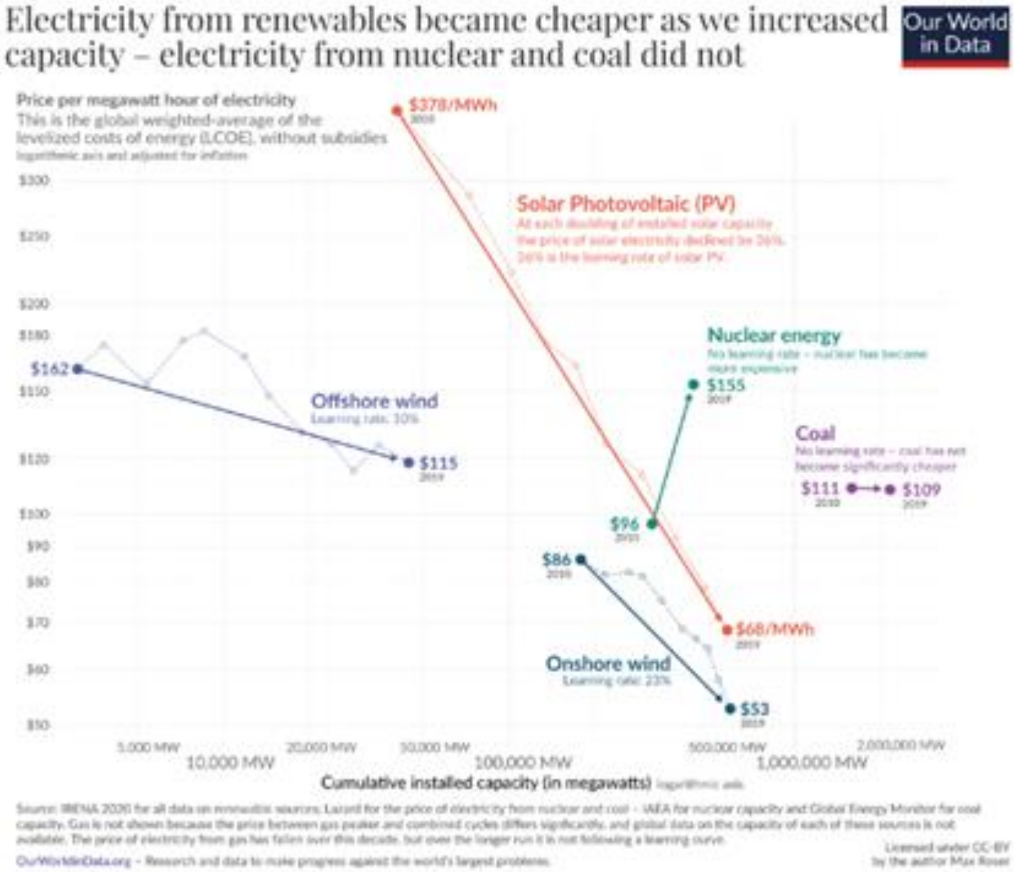
Baseload power refers to the minimum amount of electric power needed to be supplied to the electrical grid at any given time (Hanania, Stenhouse & Donev, 2020). Day to day trends of power usage need to be met by power plants, fossil fuels provide most of this base load power. Therefore, there are base load power plants like coal-fired power plants which provide the minimum needed electricity, and peaking power plants which meet the fluctuating needs (also called non base load power plants) (Hanania, Stenhouse & Donev, 2020). Most of the base load power is currently available only in the form of fossil fuel power plants and all the other alternatives involve a higher LCOE than SBSP.

Figure 4: LCOE rate comparison (Frazer-Nash Consultancy Ltd, 2021)



LCOE for Plant commissioned in 2040, using technology specific hurdle rates, NOAK[4] (unless specified) 2018 prices. Comparison data taken from Electricity Generation Costs 2020 Report.

Figure 5. LCOE rate comparison including learning curves (Roser, 2020).



Launch costs

As launch costs are the next important factor to consider in the equation, it will be prudent to analyse whether it will be economically feasible in the given timeline to achieve an operational system within the desired costs. According to the Ludwig-Bölkow-Systemtechnik GmbH (LBST) consortium's Earth and Space-Based Power Generation Systems – A Comparison Study report, the launch costs at which SBSP will break even with terrestrial solar power is 750 EUR/kg for 5 GWe of a system with electricity storage via hydrogen which will cost EUR/kwhe of 0.082 (LBST Consortium, 2005). Currently, SpaceX's heavy lift launch vehicle, Falcon Heavy, has the cheapest launch cost of $1500 /kg (1310 EUR/kg) which means a 43% decrease in costs by 2040 (Roberts, 2020). Since the commercial space sector has been expanding quite rapidly with the launch costs of Starship, also under development by SpaceX, estimated to be as low as $10/kg payload delivery cost for a 150-ton payload ($1.5 million per mission) and a high flight rate factored in, it seems to be that the launch market could become more commercially feasible in parallel to the development of this technology if research and development starts for SBSP starts now (Zafar, 2020).

Power density and energy conversion efficiency

The next point to consider is the conversion efficiency of the technology that converts sunlight to electricity, identified by Musk as being a barrier to the viability of SBSP. A paper by Zunaira Nazir calculates the efficiencies of space based and terrestrial solar power. The power density after conversion losses for SBSP where the incoming energy was taken to be 1367 W/m^2 was calculated to be 202.19251 W/m^2, giving a total end to end efficiency of 14.79% (Nazir, 2018). For terrestrial solar power the power density was calculated as being 66 W/m^2 with end-to-end efficiency being 4.83% which is mentioned to agree with National Renewable Energy Laboratory (NREL)'s efficiency predictions (Nazir, 2018). From the results it is evident that SBSP has a higher power density and a more efficient conversion rate compared to terrestrial solar power. Due to its reliability and the predictable nature of power generation output reducing during eclipses it offers a considerable advantage to terrestrial power.

Technical and investment costs

The LBST report further broke down the technical and investment costs for the system excluding the launch segment and operation and maintenance costs present in figure 6. It further calculated the percentage of investments that each segment of the system might take (figure 5). The data presented above shows the high capital costs that are required for the installation and implementation of the SBPS system for the range from 500 MW to 500 GW base load scenarios. The conclusion from the data presented is that there are high capital costs, with the majority of the costs going to the space segment. The percentage of costs going to the space segment and the ground segment which are the two main components of space based solar power are present in figure 5. Due to the low maturity of the technology and no demonstration plant available, coupled with the high non-recurring costs, public funding would be necessary if the project is to be implemented large scale and in the desired time frame.

Figure 6: Cost percentage divisions based on segments (LBST Consortium, 2005)

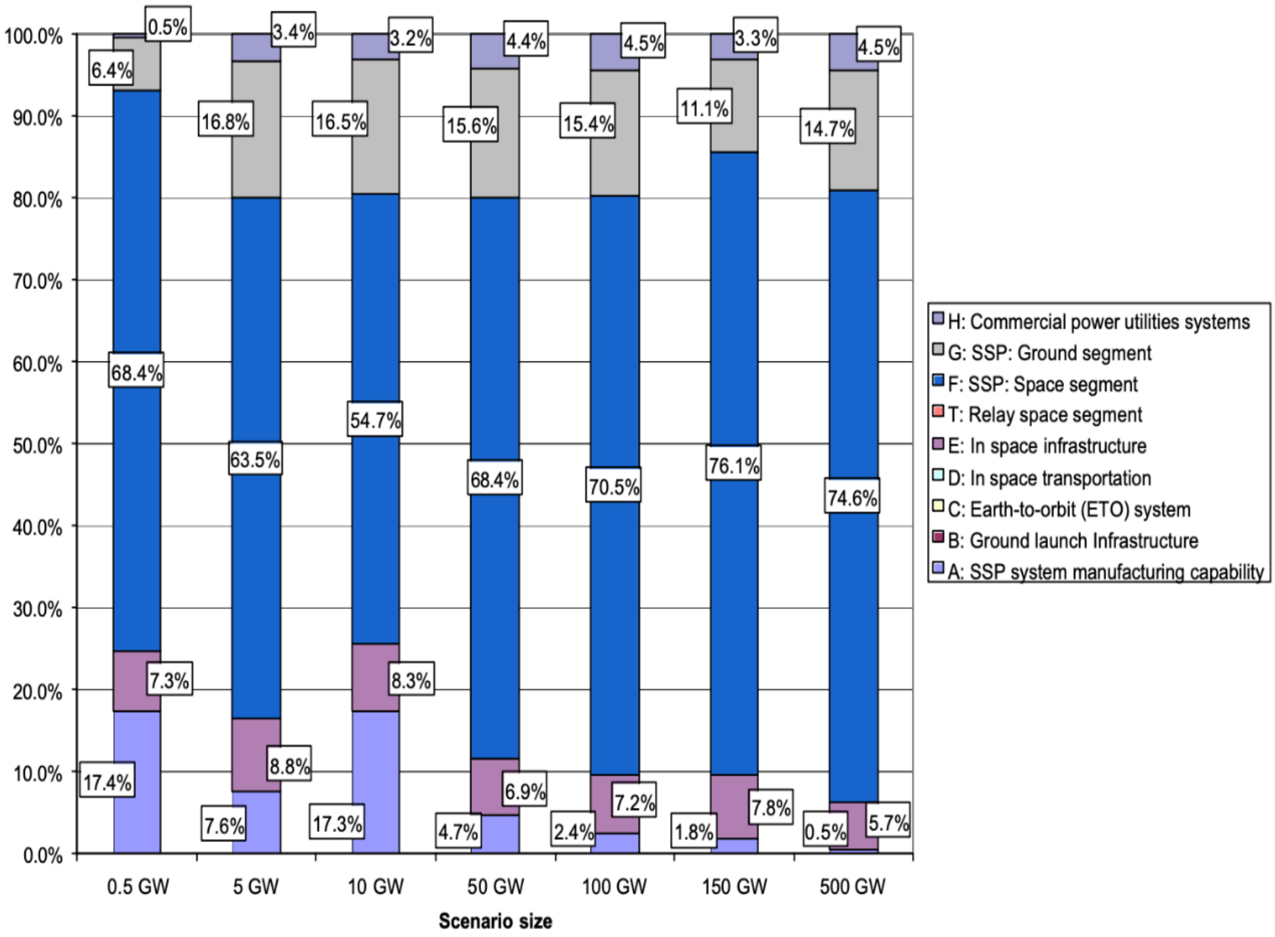
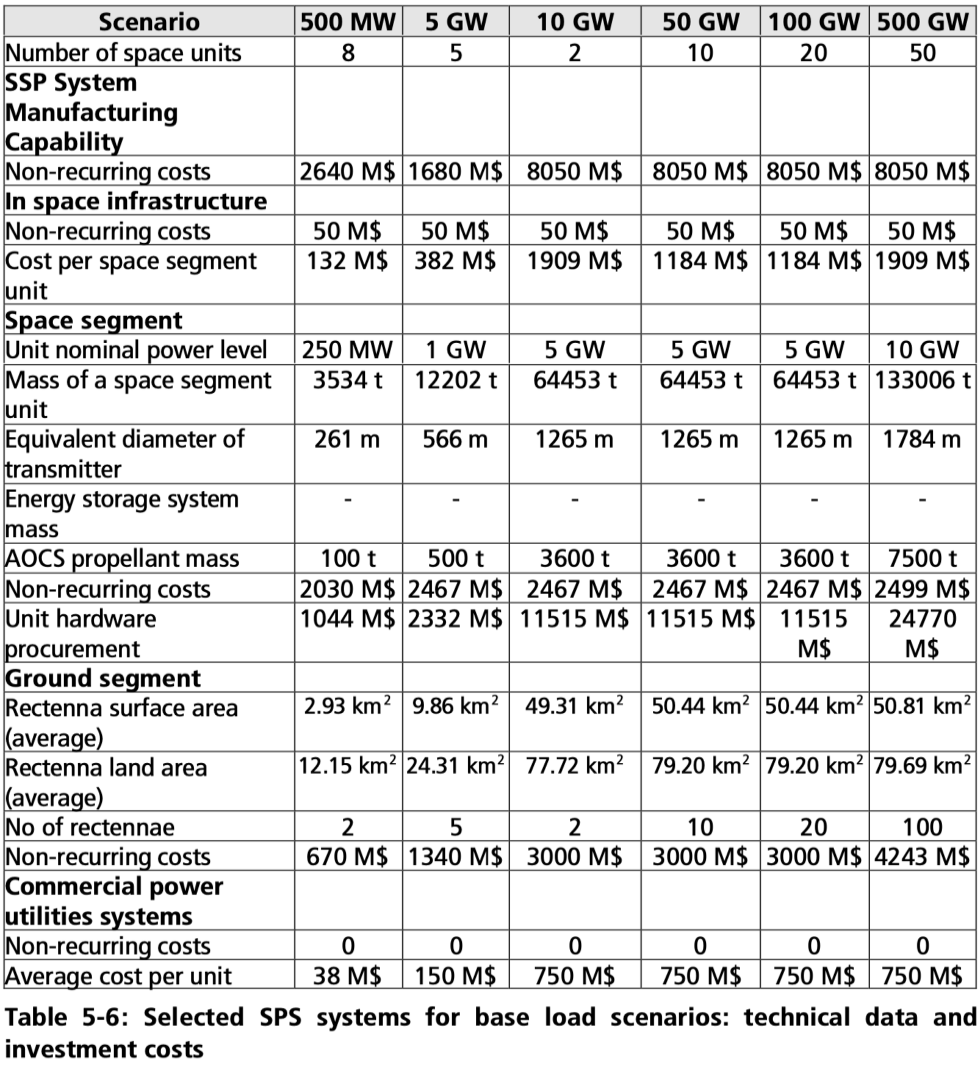


Figure 7. Technical and investment cost (LBST Consortium, 2005)



Scenario	500 MW	5 GW	10 GW	50 GW	100 GW	500 GW
Number of space units	8	5	2	10	20	50
SSP System Manufacturing Capability						
Non-recurring costs	2640 M$	1680 M$	8050 M$	8050 M$	8050 M$	8050 M$
In space infrastructure						
Non-recurring costs	50 M$	50 M$	50 M$	50 M$	50 M$	50 M$
Cost per space segment unit	132 M$	382 M$	1909 M$	1184 M$	1184 M$	1909 M$
Space segment						
Unit nominal power level	250 MW	1 GW	5 GW	5 GW	5 GW	10 GW
Mass of a space segment unit	3534 t	12202 t	64453 t	64453 t	64453 t	133006 t
Equivalent diameter of transmitter	261 m	566 m	1265 m	1265 m	1265 m	1784 m
Energy storage system mass	-	-	-	-	-	-
AOCS propellant mass	100 t	500 t	3600 t	3600 t	3600 t	7500 t
Non-recurring costs	2030 M$	2467 M$	2467 M$	2467 M$	2467 M$	2499 M$
Unit hardware procurement	1044 M$	2332 M$	11515 M$	11515 M$	11515 M$	24770 M$
Ground segment						
Rectenna surface area (average)	2.93 km^2	9.86 km^2	49.31 km^2	50.44 km^2	50.44 km^2	50.81 km^2
Rectenna land area (average)	12.15 km^2	24.31 km^2	77.72 km^2	79.20 km^2	79.20 km^2	79.69 km^2
No of rectennae	2	5	2	10	20	100
Non-recurring costs	670 M$	1340 M$	3000 M$	3000 M$	3000 M$	4243 M$
Commercial power utilities systems						
Non-recurring costs	0	0	0	0	0	0
Average cost per unit	38 M$	150 M$	750 M$	750 M$	750 M$	750 M$

Table 5-6: Selected SPS systems for base load scenarios: technical data and investment costs

Risk assessment

The last factor to analyse are the effects and implications of microwave transmission. Microwave transmission from space is already happening via communication satellites, however, there are stringent limits to the power densities that can be transmitted, and the public concern over health hazards is an important point to consider (LBST Consortium, 2005). This is a very important factor as shown by the recent destruction of 5G towers due to misinformation and fear over the new technology (Satariano & Alba, 2020). The architecture of communication satellites and solar power satellites are very similar, with both having the components mentioned in the space segment, with the key difference being that the latter will be much larger and will transmit the solar power directly via microwaves instead of amplifying and transmitting radio and microwave signals and using solar cells to generate power (Flournoy, 2012).

The procedures to launch a power satellite to geostationary orbit are also the same as those needed for launching communication satellites (Flournoy, 2012). An extensive risk analysis of transmitting microwave power was conducted for the European Space Agency (ESA) study, noting that there are very high potential safety risks prevalent in the event of a failure in beam traction, especially for systems which transmit large amounts of power via microwave to earth – such as 5 or 10 GW solar power satellites. "To reduce the impacts of such an accident caused by failure of the microwave beam a highly reliable emergency shut down of the power transmission via microwave must be proven and guaranteed for the SPS systems" (LBST Consortium, 2005). It further stated that a technical study on the dangers of microwave radiation exposure to vegetation, animal and human health were critical but was beyond the scope of the study. However, in a study conducted by Betancourt, it was stated that SBPS systems have power densities well within safe limits at the planet's surface and that microwaves used in space solar power have no ionizing effect and therefore there is no danger of cancer or any other genetic alterations (Flournoy, 2012).

CONCLUSION

The main global climate change target is to achieve net zero by 2050. To do so, it is necessary to transition our current electricity sources to renewable energy. While sources such as terrestrial solar power and offshore wind, hydrothermal and geothermal can all be used, they only offer non-base load power as they are volatile sources of energy and furthermore are dependent on time, weather and location. To offer base load power, there are only two alternatives to SBPS, nuclear and biomass, and from this study it can be seen that SBPS is the more viable alternative. Moreover, within the timeline given, it is shown in figure 2 that if a project is implemented it can be completed by 2050, thus achieving climate goals.

To conclude, this study has offered an overview of the climate crisis, a background on SBSP, the economic feasibility of SBSP in terms of timeline and costs and a risk assessment of the microwave transmission. While there are many more factors to consider such as the transportation of the satellite system to geostationary orbit, the profitability and the net benefit of the new technology to all the stakeholders involved, these are the main factors when deciding if an energy system is viable.

Overall, from the research the author found that given current global economic and climactic conditions, this system is both technologically and economically feasible by 2050 with the primary constraint being the high capital costs and low maturity of technology thus needing public funding at the first phase. This system has also been found to be the only renewable alternative that has a LCOE comparable to current renewable energy which offers a system that can supply base load power to the electric grid. The main calculations for the efficiency of the system conclude that such a system is more efficient than terrestrial solar power and could offer base load power generation capacity. The paper does not contain a return-on-investment calculation as the study attempts to prove only the economic feasibility of the system and does not include calculations pertaining to investment decisions. In a nutshell, this system is currently economically feasible if a public-private sector could pursue the development. This energy system also offers a great opportunity for international collaboration as climate change, the space industry and the energy crisis are all truly global issues. Another advantage of pursuing SBSP is that the commercial space sector is growing at a rapid pace, just as how the communication satellite sector revolutionized communication on Earth, this is a technology that would be highly beneficial to those on Earth while simultaneously expanding the space economy.

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Zafar, R., 2020. "Elon Musk Reiterates Insanely Low Starship Launch Costs Of $10/kg". [online] Wccftech. Available at: https://wccftech.com/elon-musk-starship-launch-cost-reiterate/All references cited in the text must be listed at the end of the text under the 'References' heading, and all references listed must be cited in the text. The list of the references should be in alphabetical order, as per the Harvard system.