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An Investigation into the Challenges and Opportunities of Space-Based Solar Power and its Potential in Aiding the UK to Obtain Net Zero

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Abstract

The United Kingdom (UK) is currently facing an energy crisis – with rising prices, security of supply, coupled with a rising demand for energy. As a result, the UK must enhance its energy capabilities and provide more home-grown renewable energy to its four nations. In addition, with the creation of the Net Zero Strategy, the UK has targets in place to reach net zero gas emissions by 2050. Space-based solar power (SBSP) is an innovative renewable technology that has the potential to offer a renewable energy source, while helping the UK to achieve its net zero ambitions. The aim of this research was to investigate the opportunities and barriers of SBSP and its potential in aiding the UK to obtain net zero. The research was undertaken using a qualitative approach. Qualitative data was retrieved as a result of undertaking semi-structured interviews with 6 stakeholders within the SBSP industry. The data collected confirmed that net zero is important to achieve, however more has to be done than just achieving net zero. Robotics was identified as being the biggest technical challenge, with wireless power transmission being highlighted as an opportunity. The initial cost of investment is considered to be the biggest economic challenge, however new jobs will emerge as a result of a space and energy sector. From undertaking data analysis, it was recognised that there is a lack of legislation in the space sector and as a result, eco-design is more difficult to incorporate. Nevertheless, eco-design has been found to be an essential component in the design of SBSP systems to mitigate their environmental impacts before it is too late. It was concluded that legislation is required for the space industry as a whole, if it is to achieve long-term sustainability. Recommendations have been made for further research which involves SBSP professionals being provided with eco-design training so as to aid the obtainment of net zero in a sustainable manner.

Keywords: Space-Based Solar Power; Eco-design; Net Zero; Life Cycle Assessment

Acronyms/Abbreviations

COPUOUS Committee on Peaceful uses of Outer Space
EIA Energy Information Administration
ESA European Space Agency
GEO Geostationary Earth Orbit
GHG Greenhouse Gas
IPPC Intergovernmental Panel on Climate Change
kWh Kilowatt Hours
LCA Life Cycle Assessment
LCSA Life Cycle Sustainability Assessment
PV Photovoltaic
SBSP Space-Based Solar Power
SEI Space Energy Initiative
SPS Solar Power Satellites
SSD Strathclude Space Systems Database
TRL Technology Readiness Level
UK United Kingdom
UN United Nations
UNOOSA United Nations Office for Outer Space Affairs
WPT Wireless Power Transmission
GWP global warming potential

1. Introduction

The United Kingdom (UK) is currently facing an energy crisis and the demand for electricity is only increasing – especially with the rise of electrification [1]. By 2035, electricity demand is projected to increase around 40-60% compared to the current demand for electricity [2]. In a report produced by the Office for National Statistics [3], it was outlined that to power its four nations, the UK currently imports a vast amount of its energy – highlighting that there was an increase of 312% for imported gas into the UK in 2021, in comparison to 2020 figures. The UK imported £19.6 billion of gas alone in 2021. However, also for 2021, only £3.4 billion was exported [3] – highlighting the UK bring, and buy, significantly more power into the UK than what they sell to other countries. As of 2022, 75% of the UK's energy supply is derived from fossil fuels [4]. The UK is heavily reliant on fossil fuels to deliver energy to its four nations, however with the climate change emergency and the net zero target only getting closer, now is the time to invest in new renewable technology – such as space-based solar power (SBSP). In 2021, the UK Government published the Net Zero Strategy [2]. Outlined in the Net Zero Strategy, (and the main goal of the document) the government has highlighted that the UK "is committed to reaching net zero gas emissions by 2050" [2].

SBSP is a renewable energy concept of collecting sunlight in space through solar power satellites (SPSs) and wirelessly transmitting this energy down to earth to be received by a rectifying antenna (rectenna) on ground. The power is then transmitted to the grid to be distributed. Peter Glaser, a former engineer at National Aeronautics and Space Administration (NASA), constructed a SPS engineering design in 1968 – the first of its kind [5], which can be viewed in figure 1.1 below:

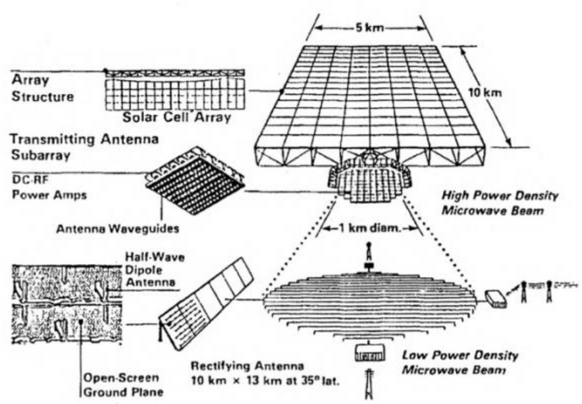

Figure 1.1: Peter Glaser SPS Design [6]

Compared to more established technologies such as terrestrial solar or wind energy, SBSP is still relatively small. However, it has a number of advantages over terrestrial technologies: SBSP offers baseload, continuous energy generation due to always facing the sun and can offer the UK energy stability [7]. Ground-based renewables offer intermittent energy, rely on weather conditions and can at times be dependent on time of day (day or night) [8]. Furthermore, a vast amount of land is required to develop these ground-based technologies - compared to SBSP, which offers a higher output of power "with substantially greater land use efficiency (GW/km2)" [8].

The use of space must be seen in an international context. To date, there are no legally binding documents on the sustainable use of outer space. However, there are guidelines which were adopted by the 'Committee on Peaceful uses of Outer Space' (COPUOUS) of the United Nations (UN) in 2019 [9]. The guidelines outlined the "long-term sustainability of outer space activities" - although these are not law [9]. In addition, in an attempt to make space systems as eco-friendly as possible, the European Space Agency (ESA) [10] has highlighted that an 'eco-design framework' will be created. The framework will include recommendations (for example, in spacecraft design) to be used by space agencies towards space missions as well as methods (including systems and tools) to evaluate the environmental impact of projects such as undertaking Life Cycle Assessment (LCA) [10].

Although SBSP has the potential to act as an enabler for the UK achieving net zero, it is crucial to take economic and technical aspects of the technology into consideration. To fully develop SBSP, high initial start-up costs are involved which will require investments from the public sector – and eventually leading to investment from the private sector [11, 12]. In addition, there have been concerns with certain technological aspects of SBSP such as the efficiency of wireless power transmission (WPT) [11]. To reach the net zero target in a sustainable manner, without compromising the space or earth environment, eco-design is an important aspect of the design stage of space systems that must be considered. Eco-design is the process of mitigating environmental impacts at each stage of a life cycle, during the design phase - and as early as possible [13]. To help with decisions, LCA is a tool to analyse environmental impacts during a product or system's life cycle, which then allows for adaptations to be made to limit impacts [14].

This research project will include an analysis of the UK's pathway to net zero, an overview of the SBSP concept, critical evaluation of the economic and technical feasibility of SBSP as well as discussing the importance of eco-design to minimise environmental impacts when developing technologies such as SBSP.

1.1 Objectives

The objectives of this research project are:

- To critically appraise Net Zero as an achievable Strategy in the UK;
- To determine the potential of how SBSP can act as an enabler to achieving UK energy and net-zero polices;

- To examine the technical and economic challenges and opportunities associated with

  SBSP;

- To evaluate how eco-design can help mitigate environmental impacts of SBSP;
- To undertake interviews with stakeholders in the SBSP industry in order to examine the barriers and opportunities associated with eco-design.

2. Literature Review

2.1 The UK's Pathway to Net Zero

Over the next 30 years, the global demand for energy is set to double [12]. The U.S Energy Information Administration (EIA) [15], estimated that by 2050, global energy generation will increase to around 45 trillion kilowatt hours (kWh) (as can be seen in Figure 2.1 below) - along with the current energy crisis and climate change emergency, the UK must adapt to renewable technologies to generate this energy.

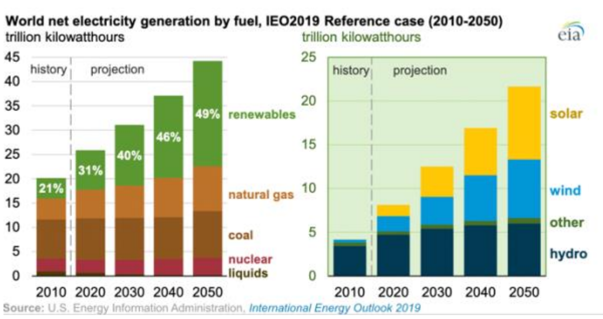

Figure 2. 1: Global Energy Demand from 2010 to 2050 [15]

As can be seen in the bar graphs by the EIA, energy generation is set to more than double in the next 30 years, confirming the previously mentioned statement from the Frazer-Nash Consultancy [12] – not to mention 2050 being the year of the net zero target.

A report conducted by the Intergovernmental Panel on Climate Change (IPCC) [16], found that to avoid the effects of climate change, the global temperature must be limited to 1.5 degrees celsius above pre-industrial levels. For this to be possible, the UK must move away from fossil fuels. The Net Zero Strategy was created in 2021 by the UK Government to eradicate the use of fossil fuels and move towards a lower carbon alternative with the use of renewable energy sources [2]. The role of net zero is to limit greenhouse gas (GHG) emissions to zero as far as possible - with emissions that remain in the atmosphere being naturally re-absorbed by carbon sinks such as plants and oceans [17]. The reason behind this is due to GHG's causing the temperature of earth to rise. Rising temperatures in turn has catastrophic impacts, resulting in environmental effects such as rising water levels [2].

In the UK's Net Zero Strategy, various sectors of the economy are highlighted with their corresponding plans to reduce emissions, but the space sector as a whole has not been mentioned. Therefore, it is clear that there is a gap in regards to SBSP and how space can be used sustainably to help with net zero. Although SBSP is not addressed in the Net Zero Strategy, the government have acknowledged there are new technologies that have not yet been explored that could drive the pathway to net zero emissions and have mentioned they will adapt and respond to these new technologies as they emerge [2] - suggesting there is an avenue for SBSP.

2.2 What is Space-Based Solar Power?

Outlined in a study by Wilson, et al. [18] the concept of SBSP is to launch a SPS system into orbit to collect rays from the sun. In addition, the study outlined that in geostationary earth orbit (GEO), a SPS system can generate power for 24 hours each day, every day, with the only exceptions being made "during the vernal and autumnal equinoxes" [18]. This is when the system moves "directly into the Earth's shadow for a maximum of 72 minutes at local midnight" [18]. The vernal and autumnal equinoxes each happen once a year, therefore, the only time a SPS system will not generate any power will be during this time, for a maximum of 72 minutes. Thus, it is unknown precisely how much time an SPS system will not generate any power as it could be lower than 72 minutes, depending on how long the equinox occurs for.

An SPS system is effectively large satellites which have solar cells (also known as photovoltaics) installed on them, to collect energy from the sun [19]. The sunlight collected is then transformed into microwaves through the use of photovoltaic (PV) arrays, allowing the power to be converted to energy and transmitted to earth though WPT [18]. WPT allows energy to be transferred from one point to another throughout space and beamed down to earth without the use of wires [20]. A rectifying antenna (rectenna) is a receiver on earth's ground which then collects the energy beam [21] this is then transferred to the power grid [1], creating a supply of electricity. An example rectenna can be viewed in figure 2.2 below:

Figure 2.2: Example rectenna [21]

It is also important to recognise the technology readiness levels (TRLs) of SBSP. TRLs are a framework used to assess and communicate the maturity and readiness of a technology – allowing for any technological risks to be identified [22]. A report by Frazer Nash Consultancy [23], outlined that at present, the UK has limited experience in the production and manufacturing of rectenna which are key elements of the SBSP concept. Therefore, this capability would need to increase significantly in order to meet the goal of contributing to the UK net zero emissions goal by 2050. It was also identified that there is limited available data in regards to experience with operating robotics in orbit, therefore this could also pose significant difficulties to the technological readiness of SBSP [23]. However, although the TRLs are low for these elements, it was highlighted that there would be a high level of difficulty involved for advancing the technology, but by 2050, they could be technically feasible [23].

2.3 Economic and Technical Feasibility of Space-Based Solar Power

For a system to be fully sustainable, it is important to note the economic and technical sides of SBSP. For SBSP to become commercially viable, initial investments from the government will be necessary. Frazer-Nash Consultancy [12] estimated that the cost of developing SBSP in general, would be around £16.3 billion – in which £350 million of that would be required by the public sector to finance Phase 1 of the space mission. Studies [11, 12] found that investment from the public sector is required for the technology to fully develop, which could then lead to private investors offering funding. Economic gain to the UK would transpire but only if SBSP is invested in for a few years [12].

The UK could benefit economically from SBSP through exporting energy to other countries. A study by Aastha, et al. [24] confirmed this, by stating a benefit to SBSP is its capability to “direct power from a collecting satellite to different surface locations”, therefore the UK could export this energy which would generate economic gain – meeting the UK’s energy demand as well as benefiting from exporting to other countries. Making the switch to SBSP will not only be economically beneficial to the UK, but it will also help to eradicate the use of fossil fuels, reducing if not eliminating, gas imports to the UK – therefore supporting the government's goal of becoming net zero by 2050.

In the Net Zero Strategy the government stated that “while there are significant costs in reaching net zero, the cost of inaction is much higher” [2]. This statement by the government suggests that there is a need to move towards new methods of energy generation - regardless of the cost associated. Thus, although SBSP is costly to initially invest in, not investing in sustainable energy could impact the UK in many ways - such as decreased energy security and increased carbon emissions as a result of having a reliance on fossil fuels.

With the technical side of SBSP, the size of the rectenna on earth could pose as a threat due to the vast amount of land that will be required. The rectenna will have to be developed to receive the energy through WPT. A study by Jakhu and Pelton [25], highlighted that the size of a rectenna could range anywhere between 1 kilometre to 10 kilometres. Although there is potential for rectennas to be extremely large structures, with renewable sources such as wind, turbines will have to be continuously developed to keep up with the rising energy demand – which ultimately will take up vast amounts of land. Even with the rectennas size, less land will be used than other renewable sources. A study by Dotson, et al. [1] highlighted that terrestrial wind and solar energy present challenges in achieving net zero as a result of the land-use that will be required for “large-scale deployment” of infrastructure that will be essential to match energy demand. They went on further to state that SBSP “presents an enticing alternative” [1].

A study carried out by Jenkins [11] has outlined that one of the main technical challenges of SBSP is in relation to WPT – specifically on the efficiency of the beam. This was echoed by Barman, et al [26] in which the low maturity of WPT was emphasised by explaining WPT has yet to become a technology that is viable. Therefore, there have been no significant technological improvements in at least 10 years in regard to WPT. As a result, demonstrations at scale will be required to determine if WPT is an effective method for beaming power back down to the UK [11].

2.4 Importance of Eco-design within Space-Based Solar Power

There are many factors that should be considered when developing a SBSP system – from the choice of materials during the design phase, to the use of propellants during the launch of the system. This is when eco-design should be considered. Chanoine [13] defined eco-design as *"a preventive approach to mitigate the environmental impacts of a product (good or service) as early as possible in the design phase"*. Eco-design can help with identifying what environmental effects can occur during every mission phase which can lead to changes in the design of a system to mitigate these effects.

A tool to help with decision making during the eco-design process is LCA - which is standardised by the International Organisation of Standardisation (ISO) [14]. The importance of LCA is highlighted in ISO 14040:2006, which outlines the framework and principles associated with LCA [14]. The LCA method is process-based and analyses the environmental impacts of a product or system from material extraction to end of use disposal, monitoring the whole life cycle – essentially from 'cradle to grave' [13]. The whole life cycle of a space mission is design, manufacture, launch, use and disposal [10]. With space missions, the impact categories which can be analysed include, but are not limited to, ozone depletion; environmental and human toxicity; resource depletion and climate change [27]. Each of these impacts will be quantified at every point of the life cycle.

The figure below outlines the method of LCA from 'cradle to grave' along with identification of the impact categories previously mentioned [28].

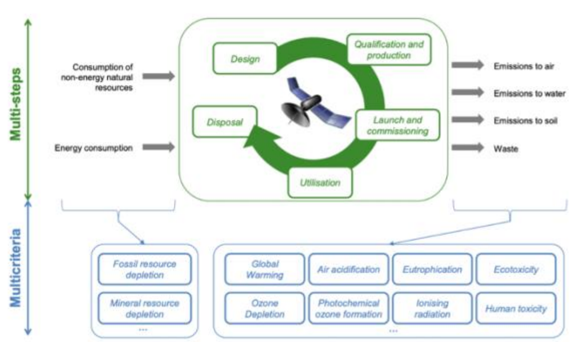

Figure 2.3: Visual Representation of LCA Method [28]

As can be seen below in figure 2.4 there are many phases to a space mission [13]. Therefore, environmental impacts will have to be quantified at each mission phase. Thus, LCA must be carried out at each phase so as to evaluate the potential impacts to the environment that may be caused from design to disposal.

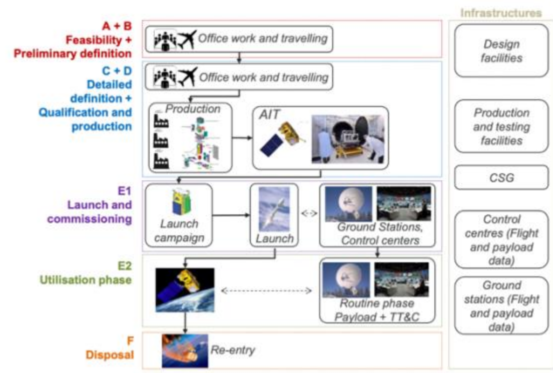

Figure 2.4: The System Boundaries of a Space Mission for LCA [13]

The LCA method allows for significant environmental impacts to be located at any point of the life cycle [14] - therefore, the system or product can be altered to mitigate the environmental impacts before it is too late, without compromising the overall performance of the system and avoiding shifting the burden. Despite LCA being a key tool in quantifying the environmental effects of space missions, it does not consider the economic and social impacts. However, Life Cycle Sustainability Assessment (LCSA) is a recently developed environmental management tool which can measure the impacts of all three (environmental, economic and social), thereby incorporating environmental and social LCA as well as life cycle costing [29].

Although applying LCSA would help develop a space system to its optimum sustainability, it has been notoriously difficult to do so [18]. This is due to the unique nature of space missions (such as the specialised materials used) and conventional databases not having the data required to carry out the analysis fully (Wilson et al, 2020). However, an LCSA database has been created called the Strathclyde Space Systems Database (SSSD) – specifically to analyse the impacts of space missions [18]. With the creation of the SSSD, hotspots of space missions will be identified during the design process, which will allow for adaptations to be made resulting in improved sustainability of space systems [18].

ESA is an intergovernmental organisation, which has 22 member states – the UK being one of them, with the aim of developing Europe's investment in space and capability [30]. The United Nations Office for Outer Space Affairs (UN-UNOOSA) held a conference in September 2022 on methods to mitigate and adapt to climate change whilst simultaneously protecting Earth [31]. ESA were the hosts of a talk held at the UN-UNOOSA conference, which was focused on LCA and eco-design of space missions and was delivered as eco-design training [10]. Moreover, in 2012, ESA launched the 'Clean Space Initiative' in order to promote the use of LCA to aid eco-design [32]. In addition, ESA hosts 'Clean Space Industrial Days' in which eco-design is a distinct theme, with talks centered around LCA [33]. Thus, it is evident that LCA is becoming more widely used in the space sector due to the benefits it can provide. As a result of ESA bringing attention to eco-design and LCA, this will emphasise its importance to organisations and professionals.

In a study carried out by Maury, et al [32], it was outlined that despite LCA being an effective tool to mitigate effects to the environment, many studies previously carried out by NASA, did not actually meet ISO 14040 LCA standards due to only analysing economics and disregarding environmental impacts. They found that a number of NASA's studies, that referred to LCA, did not actually include environmental impacts, therefore providing insufficient data.

A study carried out by METASAT UK and the University of Strathclyde for the Space Energy Initiative (SEI), was based on the CASSIOpeiA concept – which is a SPS design, in which a process-based LCA was used to determine the environmental impacts with the help of the SSSD mentioned previously. The results of this study by Wilson, et al. [7], found that many SPS systems could be improved regarding their design. This means that as a result of carrying out LCA, areas that adaptation is required where able to be highlighted, particularly with the rectenna and the use of aluminium to develop it – along with the rectennas large 76.97km^2 structure [7]. Therefore, adapting the materials in order to move away from aluminium casting and steel turning could further mitigate environmental impacts of SBSP, before they are actually used in the manufacturing of the SPS – an effective method for carrying out eco-design.

The study looks at the SEI technology roadmap – in which it was identified that the life cycle carbon footprint of the roadmap was 3.22E+11 kgCO_2eq [7]. The study went on to outline that for the delivery of the UK's net zero target, the global warming potential (GWP) impact category has an added significance. The results of the study found that the 3.22E+11 kgCO_2eq carbon footprint figure has the potential to be lowered with the correct environmental design improvements [7].

The Net Zero Strategy failed to address the importance of eco-design when developing any form of renewable – not just SBSP. But for any technology to be fully sustainable, the potential adverse effects must be quantified in order to be mitigated as much as is possible for the UK to progress towards net zero by 2050.

3. Material and methods

3.1 Qualitative Research

Qualitative research examines: *"Individuals, institutions and phenomena within the context in which they occur." [34]*. Qualitative research is therefore used to answer questions and gather evidence. Therefore, qualitative research focuses on explaining and understanding the data that is collected. With qualitative research, information can be derived from various sources using a variety of methods – these include interviews, surveys, questionnaires, emails and focus groups [34]. Hammarberg et al, [35] identified semi-structured interviews as a form of interview for qualitative research. The semi-structured approach can be used to understand opinions on different topics which can therefore provide differing perspectives and allows for more of an open conversation to be had [35]. For the purpose of this research project, using semi-structured interviews to collect primary data is the most effective method.

3.2 Justification of Chosen Method

Primary information was obtained through qualitative research by undertaking interviews with stakeholders to allow for further data to be collected and provide more in-depth knowledge and analysis. The interview questions (which are outlined in section 4) were completed by stakeholders in the SBSP industry who have a breadth of knowledge on the subject area and have first-hand experience in dealing with SBSP. The participants were each sent the interview questions in advance, prior to the interview taking place. Due to SBSP still being a new area, especially with including the aspect of eco-design, there was a limited number of specialists that could have been interviewed due to the niche topic area.

A total of 6 stakeholders were interviewed. The semi-structured interviews were carried out by video call and were audio recorded – this allowed the interviews to be listened to again, helping create transcripts and aid the analysis process. The questions were designed to analyse the Net Zero Strategy, SBSP and then more in-depth with eco-design – thus the interview questions were split into three categories. Two questions were asked in relation to net zero. The questions related to net zero were asked in an attempt to ascertain the participants' views on net zero as a strategy and if they thought SBSP could help achieve net zero targets. For the SBSP section, again, two questions were asked – this was to help identify the main technical and economic challenges and opportunities associated with SBSP. However, 6 questions related to eco-design were asked as a lot of the literature around SBSP does not discuss eco-design. The purpose was to identify if eco-design is a method that can help SBSP reach its optimum sustainability and eco-design methods that can aid this. The questions were designed in a way to allow the participants to express their own views on each of the topics whilst giving answers with in-depth knowledge, to later allow for analysis of all answers. For data analysis, thematic analysis is the intended approach. This will involve identifying key themes from the answers that have been provided.

3.3 Limitations

With every research project, it is crucial to acknowledge potential limitations. The following are limitations based on this dissertation:

- Access to Literature – Firstly, as the topic of SBSP is still new and relatively unknown, this results in a lack of literature to review. Therefore, comparisons of different research documents are more difficult to undertake.
- Data Collection Process – Online interviews were carried out through video calls, which were used to collect and analyse data. This is a limitation as face-to-face interviews could have offered more of an insight into the interviewees' body language which could have resulted in a more in-depth analysis.
- Time – Contacting interviewees and organising interview times was a lengthy process. The stakeholders that have been interviewed had their own tasks to complete within their own profession, therefore, it was more of a challenge to communicate with them as a result of their busy jobs. As a result, arranging times for the interview to take place was often challenging. Other stakeholders had been contacted for interview to ensure data analysis and results were more robust. However, there was a lack of response and the time to undertake interviews was limited, which resulted in only 6 interviews being carried out.
- Sample Size – 6 stakeholders were interviewed. This is a relatively low number of interviewees – which can consequently have an impact on results due to the niche group who have been interviewed. SBSP is still a new technology and with incorporating eco-design into this research, there is a lack of specialists who are available for interview due to the nature of this topic. In addition, as the interviews were conducted with stakeholders in the SBSP industry, this can result in bias and arguments in favour of the use of eco-design of SBSP systems to help achieve net zero. Therefore, results may not be as well-rounded as they could be with more and differing opinions.

4. Results and Discussion

The semi-structured interviews were divided into themes. The first theme was the UK's Net Zero Strategy, the second theme was the technical and economic opportunities and challenges of SBSP, and the third theme was related to the effectiveness of eco-design. The data extracted from the interviews are those which are most relevant to the question and relate to key themes.

4.1 Qualitative Data Analysis

4.1.1 Net Zero

Question 1: What are your views on Net Zero as a Strategy? Do you think it is important to achieve?

Participants 3-6 replied with yes from the outset – highlighting that they strongly believe net zero is important to achieve. Participant 1 did not give a definitive answer on whether they think net zero is important to achieve, which corresponds with the participant's later explanation of *"net zero is just the first step"*. However, Participant 2 firstly explained the climate change emergency with reference to the IPPC. The participant outlined that *"if we don't want to reach the grave consequences of 2 degrees or over... the only way to do that is through Net Zero"*. Participant 2 explained that net zero is the only solution to avoid reaching the IPPC's warning of 2 degrees or over, in order to circumvent the effects of climate change.

Participant 1 and 3 both went on to express that net zero, although is important, more has to be done than just achieving net zero. In addition, participant 3 explained that they think *"Net zero is a great step in the right direction in terms of reducing carbon emissions...but I think there needs to be more focus on sustainability in general"*. Therefore, 5 out of 6 participants were in complete agreement that the Net Zero Strategy is a necessity, with 1 participant not giving a definitive answer. It can be analysed that the reason why a number of participants believe that net zero is only the first step and more must be done, is as a result of the net zero target having a goal of being achieved by 2050. It can be argued that net zero must be considered after 2050 and consider a system or products entire life cycle – not just until 2050.

Question 2: In your opinion, can SBSP act as an enabler and help reach the net zero target of net zero gas emissions by 2050? Explain why or why not.

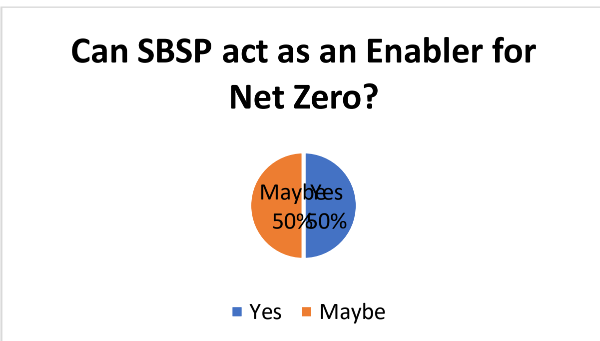

Figure 4.1 Feelings on SBSP contributing to reaching Net Zero

For half of the participants that responded with yes, their answer was immediate. This indicates that they are certain SBSP could help the UK to reach their net zero targets. However, despite the participants all being professionals within SBSP, only 50% of them believe SBSP can help achieve net zero. The remaining 50% are unsure if SBSP can or cannot help reach net zero – therefore casting doubt on the capabilities of SBSP. This highlights uncertainty amongst professionals on the full potential of SBSP.

Despite this uncertainty, participant 3 stated *"I think SBSP is one of the only ways to achieve Net Zero"*. This statement by participant 3 emphasises the importance of SBSP in helping to achieve net zero within the UK. The participant seems confident on the abilities of SBSP. The UK's pathway to net zero was explored in section 2.1 of the literature review in which SBSP was recognised as a potential renewable technology that could aid the UK in achieving net zero – therefore corresponding with the response of participant 3. In addition, also in section 2.1 it, was identified that HM Government [2] will adapt and respond to new technologies, as they emerge, that have the potential to drive the pathway to net zero emissions. From the responses by the participants, it is clear that there could be a potential for SBSP to be one of those new technologies.

4.1.2 Technical Opportunities and Challenges of SBSP

Question 3: What are the technical challenges and opportunities associated with SBSP?

Based on carrying out a SWOT analysis, it was evident that WPT is both a technological opportunity as well as a barrier. WPT was a reoccurring theme within responses, highlighting its significance within SBSP. Participant 3 and 6 mentioned that WPT is not only for beaming energy back to the UK, but it can also be used for other applications. In section 2.3, it was identified by Aastha, et al [24] that the UK could benefit from using WPT in order to export energy generated from SBSP to other countries. However, one of the biggest challenges recognised for WPT was identified by participant 2 in which they discussed in order for WPT to work, a global agreement will be required. In addition, participant 6 stated *"this needs international regulations and standards to be developed"*. Therefore, it was recognised by two participants that regulations will be required for WPT. The lack of legislation for SBSP was highlighted in section 1 and 2. This confirms there is a legislation issue and there are laws that must be created regarding the use of space and SBSP.

Robotics and in-orbit assembly was an additional theme that was recognised during interviews. Participant 1 stated that *"robotics remains perhaps the most significant technical challenge for SBSP"*. In section 2.2, robotics was identified as an area that effects the TRLs of SBSP [23]. Robotics and in-orbital assembly were identified by 5 out of 6 participants as being an obstacle. Therefore, showing that amongst stakeholders in industry, robotics is a big concern. In addition, participant 4 outlined that the robotics required for in-orbital assembly and maintenance currently does not exist. As a result of the majority of participants outlining robotics as a challenge and the sheer fact that the robotics have not even been developed yet, it is evident why robotics has been highlighted as a significant technical challenge.

4.1.3 Economic Opportunities and Challenges of SBSP

Question 4: What are the economic challenges and opportunities associated with SBSP?

From recognising the themes from responses, potentially, the biggest economic challenge to SBSP is the large costs associated with the initial investment. As discussed in section 2.3, expressed in a report by Frazer-Nash Consultancy [12], they estimated SBSP would cost £16.3 billion to develop. This corresponds with the opinions of the participants in this research project in which 5 out of 6 participants all highlighted that investment is a challenge. Participant 5 noted that a *"development programme from SBSP ends up being 10 to 20 billion"* – this figure therefore corresponds with the £16.3 billion estimation. Furthermore, participant 2 highlighted *"because they are kilometers in size, and because it will be the largest engineering challenge conducted by our species - it is going to cost billions. That is the thing that puts people off"*. This statement calls attention to the large structure of SBSP systems – so large that it has the potential to become the largest engineering project the world has ever seen. It also focuses on the fact SBSP will cost billions – linking with the cost estimated from Frazer-Nash Consultancy [12] as well as the statement by participant 5.

Although there are large upfront costs, it was recognised by participant 2 that NASA once thought it *"would be impossible to launch anything for less than $20,000 per kilogram"*. However, participant 2 continued by saying *"now, with SpaceX, we are nearer $2000 per kilogram"*. This indicates that the cost of launch has decreased significantly over the years. Participant 2 went on to explain that an enhanced economic case for SBSP will be achieved if the price for launch continues to decrease.

However, despite the fact there are large upfront costs associated with SBSP, there are opportunities that come along with this. Participant 3 mentioned that *"SBSP is going to generate a new industry, so although there is a space and energy industry - the two haven't merged yet"*. As a result, this has the potential to create a completely new industry, bringing new capabilities and an array of jobs to the UK. As a result of new jobs there will be an increase in specially-skilled workers, helping companies to grow – which is especially important in the SBSP sector due to the lack of specialists. Therefore, SBSP has the potential of being beneficial to the UK economy.

4.1.4 Effectiveness of Eco-design

Question 5: What do you think are important design aspects when thinking about sustainability, in regard to SBSP systems?

There were varying responses provided for this question, indicating that there are several important design aspects that should be considered to achieve optimum sustainability of SBSP. Participant 3 outlined that undertaking *"a proper LCA and Carbon Footprint Assessment of the system"* is an important design aspect. This was echoed by participant 2 who stated, *"we take that life cycle perspective - which is what eco-design is meant to do"*. From this statement by participant 2, it can be analysed that the role of eco-design is to take into account the whole life cycle of a system, therefore, reiterating LCA and LCSA as effective methods of eco-design. Within section 2.4 of the literature review, LCA was recognised as an effective method of eco-design by ISO [14]. Thus, as a result of the literature reviewed and the responses from participants, it is evident LCA and LCSA should be an important design consideration in regard to SBSP systems.

Furthermore, participant 1 highlighted that *"many of the same aspects necessary for cost-competitiveness are identical to those required for sustainability"*. Participant 1 went on to explain that with the likes of integrating reusable launch vehicles and using natural materials such as bamboo fiber instead of concrete and steel to manufacture systems, these are just a few design aspects that could be included for SBSP systems to be sustainable. In addition, incorporating the likes of reusable launch vehicles will ultimately mean less launch vehicles will have to be manufactured – helping not only to save materials, but also be more cost effective. As a result, it is likely that if companies undertake an eco-design approach and utilize more sustainable materials where possible, their SBSP system could in fact become more economically viable.

Question 6: For SBSP to be sustainable and have little environmental impacts, do you think incorporating eco-design into the design phase of a system could help with lowering these impacts?

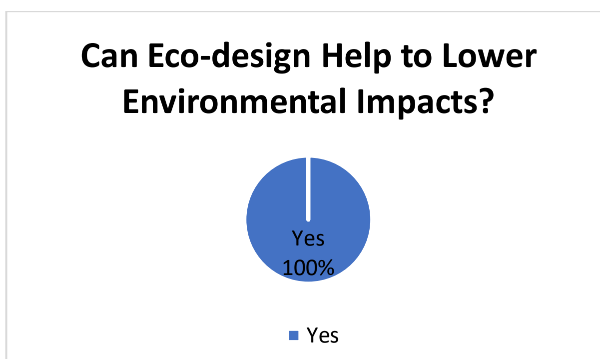

Figure 4.2: View of participants on eco-design helping to lower environmental impacts

All participant's unanimously agreed eco-design is an effective method to lower the environmental impacts of SBSP systems. Participant 6 stated that eco-design is "*absolutely essential".* This is promising as it highlights the importance of undertaking eco-design in order to create a more environmentally friendly SBSP system. participant 2 highlighted that *"80% of a products environmental impact or sustainability impact is set by early design choices"*. Given the 80% figure, this emphasises the significance of designing sustainably and calls attention to the major impact that not designing sustainably can have. Participant 2 continued by explaining it is more challenging to modify or make changes to the concept, the further along in the design process you go – stating that *"essentially the design gets locked"*.

As discussed previously, eco-design can help mitigate environmental impacts at each mission phase. Participant 2 outlined that when you are able to pinpoint where these environmental impacts and hotspots are coming from, *"then the more scope you will have for changing that design".* For that reason, aspects of the SBSP system can be changed, helping to lower environmental impacts before it is too late. Therefore, it is reasonable to assume that eco-design is an effective method to mitigate the environmental impacts that may be associated with SBSP as a result of the discussion in section 2 as well as the response from participant 2.

Question 7: What is an effective way(s) of incorporating/carrying out eco-design when developing SBSP systems?

Participant 1 had no response for this question. This could highlight uncertainties of eco-design which could outline that eco-design is not as well-known as it should be within the SBSP industry. Therefore, indicating that there is a need for professionals to learn more about eco-design, if SBSP is to be sustainable.

Participant 4 highlighted "*there needs to be an element of life cycle assessment and life cycle sustainability assessment"* as an effective eco-design method. The effectiveness of LCA and LCSA was demonstrated bin section 2.4 [18,29]. The study by Wilson, et al. [18] utilised a process-based LCA that was used to determine the environmental impacts of a SPS. The study confirmed that many SPS systems could have design improvements to perform to their optimum sustainability. In addition, LCSA was identified by Wilson [29], as being a tool that not only quantifies environmental impacts, but also the economic and social impacts. As a result of the two reports explored in the literature review and the response from participant 4, LCA and LCSA can be viewed as one the most effective eco-design methods.

Question 8: What are the main challenges of undertaking eco-design in regard to SBSP?

Question 9: What are the main opportunities of undertaking eco-design in regard to SBSP?

Questions 8 and 9 were joined together as part of the analysis process, to fully compare the opportunities and barriers.

Participant 2 and participant 6 touched on the lack of legislation within the space industry. Participant 2 stated that *"the space sector has essentially been allowed to pollute as much as they want and the reason for that is they are exempt from many legislation and regulations*". Participant 2 continued by explaining that as a result of this lack of legislation, when work around eco-design began to emerge, it was a new concept to many in the space sector as they had been allowed to pollute the space environment, without any consideration of the environmental impacts. Therefore, it can be analysed that eco-design is still a fairly new method of quantifying environmental impacts and professionals in the space sector must be more educated on the topic otherwise, trying to incorporate eco-design will be a challenging process. The lack of legally binding documents for the space sector has been highlighted in section 1 and 2 and not being included in key documents such as the Net Zero Strategy has also been explored in sections 1 and 2.

In regard to opportunities of eco-design, the responses provided from 5 out of 6 participants all link with each other. They all mentioned that eco-design will result in the long-term sustainability of SBSP as well as the space sector. Participant 4 stated *"I would say the main opportunity is that we can go on having a space sector"*. This statement provided by participant 4 really emphasises the requirement of sustainable practices within the space industry. Participant 4 went on to describe that without adopting sustainable practices such as eco-design, the space sector will struggle if they fail to address and adapt to climate change. As a result, it can be analysed that eco-design could help the long-term sustainability of the space sector by quantifying environmental impacts.

Reduced environmental impacts through life was one of the opportunities identified from undertaking eco-design. This was an opportunity recognised by participant 6. It can be assumed that the participant is talking about LCA or LCSA as a result of LCA quantifying environmental impacts through the entire life cycle of SBSP systems. Previously in section 2.4 within the literature review, it was identified that LCA and LCSA are both effective methods of eco-design. As a result of participant 6 recognising this as an opportunity, the importance of LCA and LCSA is reiterated. Moreover, participant 2 stated *"I personally see eco-design as being the future direction of lets say procurement in the European space industry. So, I actually think that, maybe not eco-design but certainly LCA will become a compulsory procurement requirement of all ESA contracts probably by about 2030, in my opinion"*. This response by participant 2 called attention to that in the very near future, LCA could become a non-negotiable in the design of SBSP systems. As a result, this would require all companies to carry out LCA on their systems. Therefore, it can be analysed that if LCA is to become a compulsory requirement of designing SBSP systems then more training will be required within the industry to ensure all professionals and companies are aware of the LCA process.

Participant 1 preferred not to answer these questions, stating "*while I appreciate them, I don't want to talk out of turn"*. This can outline that even as an expert within the SBSP industry, not everyone is aware of eco-design, or this could relate to a statement by Participant 2 *"I don't think many space organisations really know about their environmental impact or really care all that much about it"*. Therefore, suggesting that organisations should be doing more to understand their environmental impact. This relates back to the identification of professionals within the space sector not having an in-depth knowledge of eco-design, reiterating the need for professionals to become more educated on eco-design to reduce environmental impacts of SBSP systems. Furthermore, it could also link back to the lack of legislation within the space sector and organisations being able to get away with polluting the space environment – thus, not having to be aware of their environmental impact as there are no laws.

Question 10: Do you believe SBSP is truly environmentally, economically as well as technically feasible? And could eco-design help with all 3 categories?

Regarding the environmental feasibility of SBSP, 50% of participants believe it is environmentally feasible. The remaining 50% believe it has the potential to be environmentally feasible. However, Participant 5 outlined that they believe that there is an environmental cost associated with everything, however, they also think "*SBSP will be one of the lower impacts from energy generation"*. Therefore, from responses it is clear that SBSP does have the potential to be environmentally feasible as long as the correct assessments are carried out to mitigate potential impacts.

Every participant agreed that SBSP is economically feasible. However, participant 4 did highlight that although there have been studies that have shown that SBSP will be economically feasible, the participant believes the studies were not complete. This could indicate that further analysis should be carried out on the economic feasibility of SBSP. However, as a result of the unanimous response, it is evident SBSP has the potential to be economically feasible. In addition, participant 3 stated *"I think we are going to get to the point where it doesn't need to be economically feasible"*. Participant 3 continued by explaining that the impacts of climate change will be so severe that action will have to be taken, even if there is no economic profit. Therefore, it can be argued that economic feasibility should not be considered as an important issue.

A total of 5 participants believe SBSP is technically feasible, with 1 participant believing it possibly could be. Participant 4 outlined that there are no unknown physics in relation to the technical feasibility of SBSP, however their view remains that SBSP could potentially be technically feasible. Thus, participant 4 has doubts on the full technological capabilities of SBSP – even though the physics are known.

Half of the participants believe that eco-design can help SBSP become economically, technically and environmentally feasible. When the interview question was asked, participant 4 replied *"the answer to the second question is yes. That is definitely yes"*. Ultimately suggesting that eco-design can indeed help with 3 categories. Furthermore, in relation to the environmental feasibility of SBSP, participant 4 stated "*there is where eco-design will actually change things and confirm that it is environmentally feasible"*. This suggests that any form of doubt regarding the feasibility of SBSP, has the opportunity to be eradicated by the help of eco-design. Eco-design would recognise any potential impacts and give companies the opportunity to adapt their design and would therefore allow for studies to take place to fully confirm the feasibility of SBSP.

However, participant 1 stated that *"my personal view on eco-design is supportive, provided this does not introduce unnecessary delays"*. From this statement, it can be analysed that participant 1 would incorporate eco-design as long as it is does not take up too much time, in order to ensure deadlines are met. Therefore, it is reasonable to assume that there could potentially be many professionals and companies who hold this same view, which could be one of the reasons why eco-design is not as mainstream as it should be.

Therefore, in summary, professionals within the SBSP industry believe SBSP can be environmentally, economically as well as technically feasible – however there are further assessments that must be carried out to fully confirm SBSP's potential within these areas. There is uncertainty whether eco-design can help with all 3 of these categories, however half of participants believe it can – therefore proving there is potential for eco-design to do so.

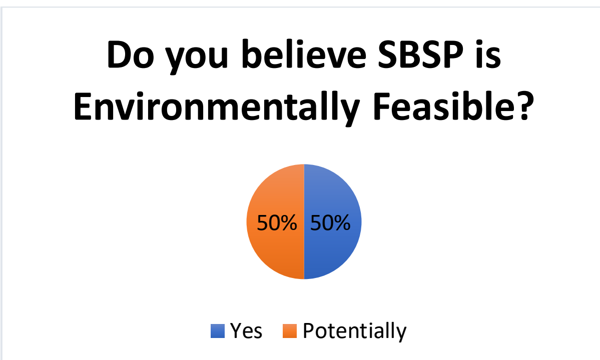

Figure 4.3: Responses to the environmental feasibility of SBSP

Figure 4.4: Responses to the economic feasibility of SBSP

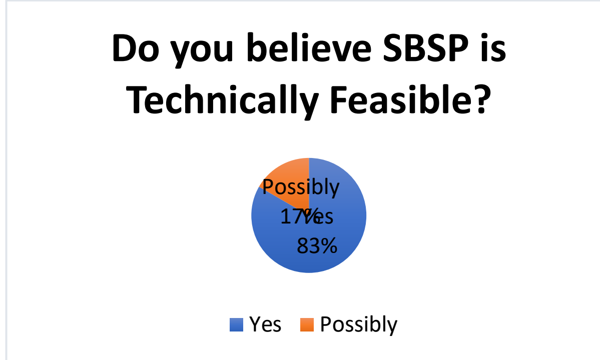

Figure 4.5: Responses to the technical feasibility of SBSP

5. Conclusions

Through undertaking interviews, it was determined that net zero is an important strategy to achieve for the UK in order to mitigate the effects of climate change. However, it was identified by professionals that more has to be done than net zero and if the targets are to be met, it will require involvement by all forms of renewable technologies – not just SBSP. In addition, it was also analysed that some professionals believe that once the target of 2050 has been achieved, net zero must continue to remain at the forefront of decision-making. Thus, net zero must go beyond 2050, and thinking about net zero must not stop once the year 2050 has been reached. SBSP is absent from the Net Zero Strategy. Nevertheless, from analysing the strategy it was recognised that SBSP has the potential to aid key policies to help the UK in achieving net zero. In addition, from carrying out interviews with SBSP professionals, it was identified that 50% of participants believe SBSP can act as an enabler for the UK achieving net zero. This shows that SBSP could potentially have the ability to aid net zero, however it also highlights uncertainty amongst professionals in the capabilities of SBSP.

The technical and economic feasibility of SBSP was explored within section 2.3 where it was highlighted by Jenkins [11] and Frazer-Nash Consultancy [12] that investment for SBSP would be one of the biggest economic challenges. This was echoed through the collection of primary data where high initial investment costs were recognised as being a key theme among responses. However, economic return will transpire after investment as a result of new skills and jobs for the UK from a joint space and energy sector. From collecting primary data through semi-structured interviews, it was identified that robotics and in- orbit assembly are the biggest technical challenges facing

SBSP. Robotics and in-orbit assembly are not yet available. Therefore, manufacturing and assessments will be required on the effectiveness of these systems. WPT was recognised as being a technical opportunity from stakeholders as well as from reviewing literature – emphasising its potential within SBSP.

From analysing second hand data, LCA and LCSA were recognised as effective eco-design methods to reduce the environmental impacts of SBSP. This was echoed by stakeholders who took part in the interview process, where LCA and LCSA were discussed for numerous questions – highlighting its importance. For eco-design to become more mainstream, there is a requirement for this to be included in strategies and policy papers. In doing so, eco-design would become a requirement for all companies within the space industry.

Semi-structured interviews were undertaken with 6 stakeholders in order to examine the challenges and opportunities associated with eco-design. One of the main findings was carrying out eco-design will allow long-term sustainability of the space sector to be achieved. Without eco-design, the space sector will face challenges in the long- term as a result of not adapting to climate change. With the incorporation of eco-design, SBSP systems will see reduced environmental impacts through its entire life cycle. The lack of legislation was found to be one of the biggest challenges of eco-design. Legislation was viewed as a challenge as the space sector have been allowed to pollute as much as they want as a result of no legally binding laws to prevent them from doing so. Thus, as there was no requirement to be sustainable, there is a need for professionals to become more educated on eco-design if it is to be incorporated when designing SBSP systems, to quantify environmental impacts.

The overriding conclusion is that SBSP has clear potential in helping the UK to obtain net zero, however until various challenges are overcome (such as the integration of eco-design) and SBSP is included in policy, it will be difficult to do so.

5.1 Further Recommendations

Although objectives of this research project have been achieved, there are still challenges of SBSP that will remain until the system has been fully manufactured and tested. Further recommendations for academia:

- Direct research findings and information towards ministers and government, in order for SBSP and the space industry to be included in policies and regulations.
- Further research on eco-design methods for SBSP systems to find out which methods would allow for the most significant changes to be made.
- Conduct research to determine which materials would be best for obtaining sustainability without compromising the overall performance of SBSP systems.

Further recommendations for industry:

- Professionals within the SBSP industry should be provided with adequate eco-design training to limit the environmental impacts of SBSP. For SBSP to become environmentally friendly, this will require experts in eco-design and professionals to have an in-depth knowledge on how to quantify their impact.
- Industry should begin to apply eco-design to all developments to mitigate environmental impacts as far as is possible. Eco-design should be applied at the very beginning of the design stage to fully optimise the sustainability SBSP systems.
- In addition, industry should be aware of their environmental impacts and ensure they know how sustainable their SBSP systems are.
- Promote the requirement of legislation for the space industry.

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