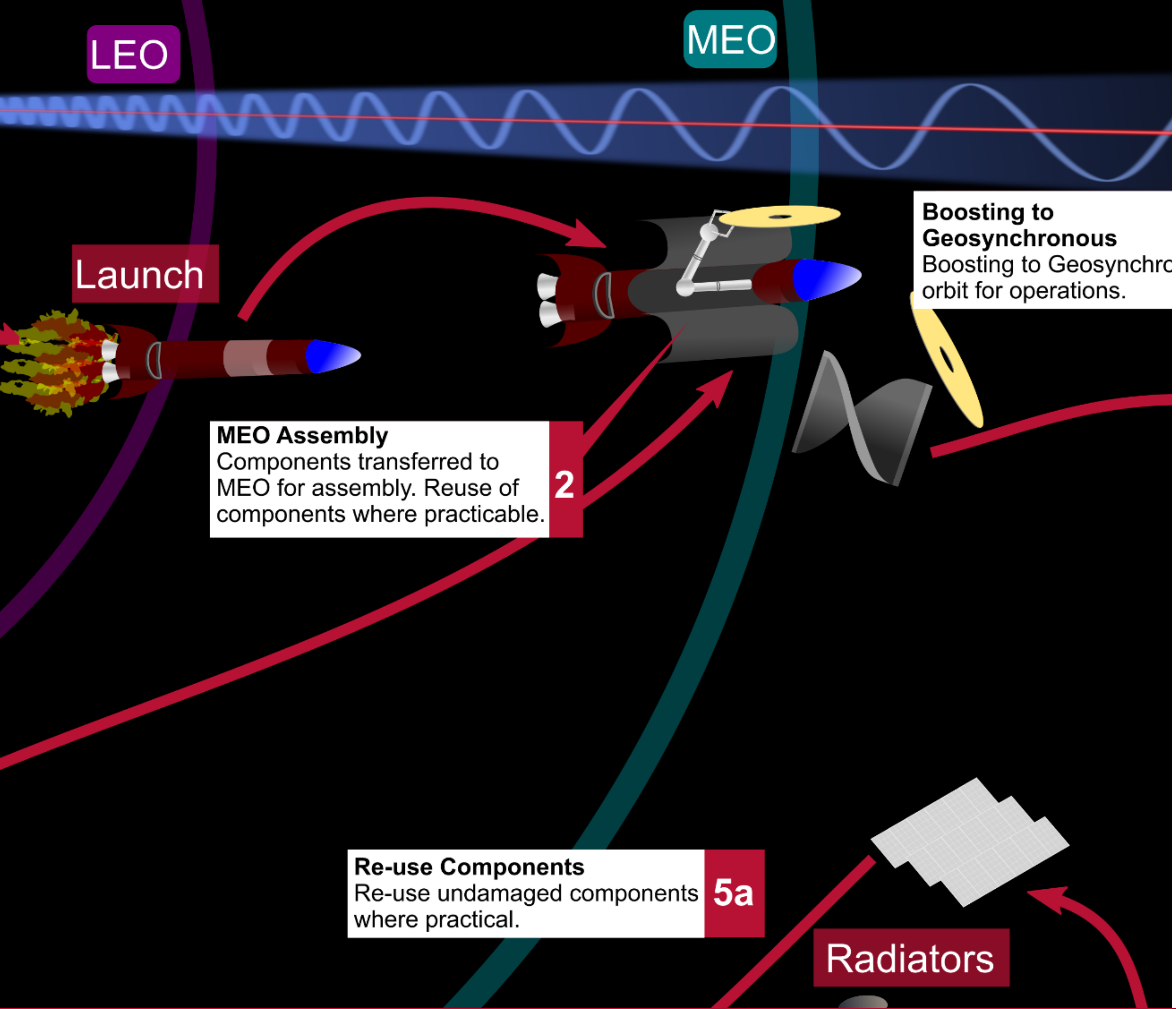

Space Based Solar Power

Summary Report

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SYSTEMS • ENGINEERING • TECHNOLOGY

Space Based Solar Power

Summary Report

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1 Introduction

1.1 Background

Space Based Solar Power concepts promise the generation of large amounts of renewable power by launching vast Solar Power Satellites (SPS) into space and beaming the power back to rectennas on Earth. Due to diffraction physics, large scale arrays delivering 2GW of power to the ground will be on the order of a kilometre in length and have masses between 2,000 and 10,000 tonnes. As of January 2020, the amount of debris orbiting the Earth exceeded 8,000 metric tonnes. A decommissioned SPS would therefore have the potential to create a step change in the mass of debris humanity has created.

There is significant interest in pursuing Space Based Solar Power (SBSP) technology, recently renewed due to the need to decarbonise the energy supply in order to achieve Net Zero goals and a recent focus on achieving energy security. Achieving Net Zero targets will require wholesale change to the European energy system and large scale investment. SBSP offers a number of potential advantages over the majority of terrestrial renewables: high-capacity factor, dispatchable power delivered across a large area.

SBSP would represent a key step in humanities progression from scientific exploration in space to exploitation of resources. Terrestrially this type of transition has typically been accompanied, at least eventually, by a greater burden of responsibility on exploiters to limit the environmental damage they leave behind after their activities. SPS operators would have a duty of care to not endanger other space users and to preserve the resource for future generations. In order to achieve this, they will almost certainly be required to sustainably decommission SPS.

Whilst there is still significant work to be done in demonstrating the technical and commercial viability of SBSP, this study seeks to understand the potential routes to decommissioning such massive structures in a sustainable and ethical manner. There is increasing focus in the space industry on regulation around sustainable decommissioning and, by the time any SPS are developed and launched, it is highly likely that they will require a sustainable decommissioning plan. To date, the majority of satellites in Low Earth Orbit (LEO) are left to de-orbit and burn up on their own. Satellites in further away orbits, such as Geostationary Orbit (GEO), are typically boosted by around 300km in 'graveyards orbits'. However, due to the increased scale of SPS over traditional satellites and greater potential for environmental damage, these options are unlikely to be viewed as acceptable.

As with any decommissioning programme, the key considerations are technical feasibility, cost and environmental impact. In many terrestrial industries, decommissioning is an under-considered part of the project lifecycle as it is typically a significant financial drain on projects and is only carried out due to regulatory requirements. However, because material in space has inherent value from its position at the top of a gravity well, it may be possible for decommissioning of an SPS to pay for itself or even generate a profit. There is an inherent tension in this economic balance: low launch costs are desirable for building an SPS however, a higher launch cost makes the value of orbital assets higher and increases the value that can be recovered from decommissioning activities.

This study has been conducted by Frazer-Nash Consultancy on behalf of the European Space Agency through the Open Space Innovation Platform (OSIP). The objectives of this study are to:

- Understand what future SPS systems may look like, how they will be assembled and what types of sub-systems they will incorporate;
- Understand how the components and materials within an SPS will degrade and fail over its lifetime;
- Generate a number of end-of-life strategies for an SPS;
- Evaluate those strategies for economic benefit and technical feasibility;

- Identify and present the characteristics of an SPS design which should be considered to enable sustainable decommissioning.

2 Work package summary

2.1 Work package 1 – Characterise an SPS

The purpose of this work package was to identify the characteristics of an SPS and the likely systems, components and materials which would be present. This information informed the rest of the study and provided a baseline. The assessment focused on two of the existing leading concept designs, CASSIOPeiA and SPS Alpha.

The generic breakdown of SPS systems shown in Figure 1 was created. This study is only concerned with the systems within the SBSP satellite boundary and not the ground-based systems. A lack of design detailed and component choice was identified, this has impacted the fidelity of the study in future work packages. Enough information was found to provide a number of useful conclusions however, specific strategies could not be assessed against a chosen design.

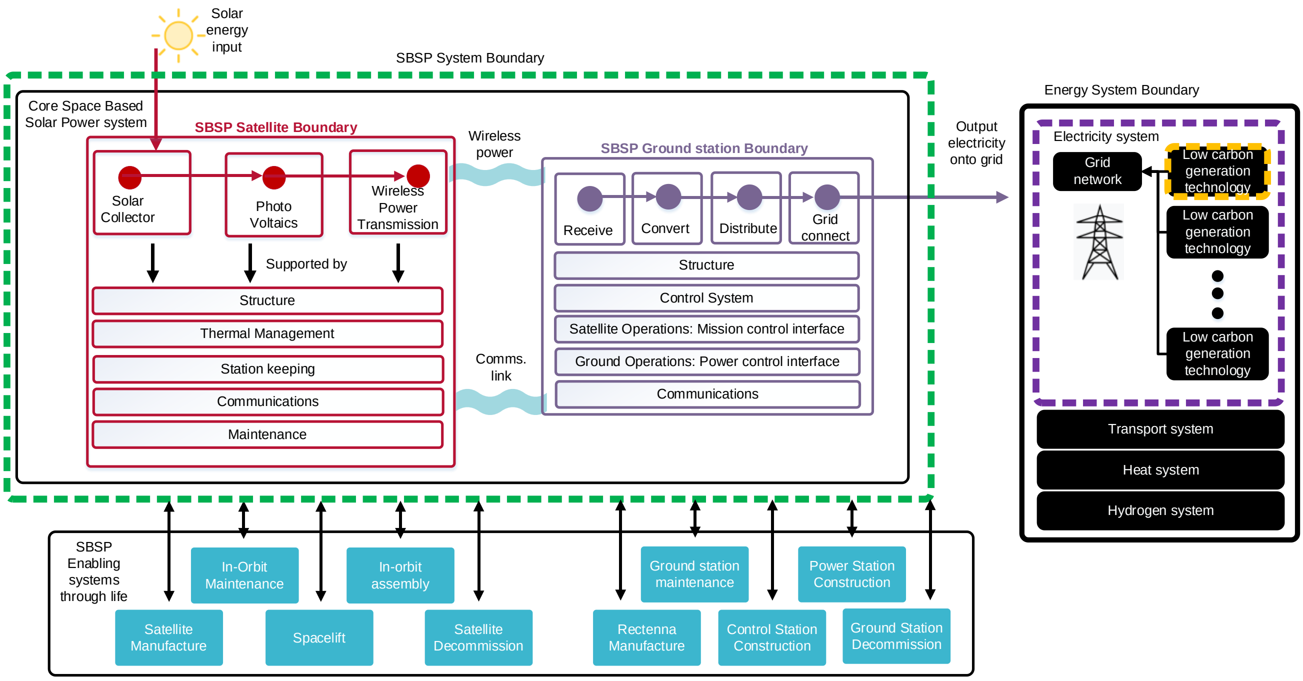

Figure 1 - SBSP System Breakdown

2.2 Work package 2 - Degradation mechanisms

This work package explored the degradation mechanisms which will affect the main groups of components and lead to the eventual end of life of the overall satellite. Understanding the approximate lifetime of an SPS will enable better end of life planning. The mechanisms affecting individual components will vary depending on the design, material choice and local component environment.

The key degradation mechanisms identified were:

- Radiation and UV
- Micro meteors and debris

- Condensation and contaminants
- Fatigue
- Thermal cycling
- Failed deployment
- Electrical faults

2.3 Work package 3 – End of life Strategies

This section identified a number of end of life strategies at a macro level for the entire SPS as well as doing a deeper dive on the circular economy 10R strategies which could be applied to individual components. The strategies were assessed during a workshop using a series of criteria including:

- Technical feasibility and infrastructure requirements
- Scheduling
- Economics
- Regulatory
- Environmental impact
- Resource preservation
- Required delta-v
- Energy Requirements
- Reliability and risk

The proposed strategies included continuous replacement, transfer to the lunar surface, a Geo graveyard orbit, propelling the SPS into space, burning it up in the atmosphere and applying the 10R strategies to individual components. Table 1 below presents a summary of the various 10R strategies and explains how they might be applied to SPS. Figure 2 provides an overview of where each of these strategies could be applied to an SPS throughout the lifecycle.

Table 1 - 10R strategies

Title	Description
R0 – Refuse	Both consumers and manufacturers can use or buy less of a good or resource to prevent the creation of waste.
R1 – Reduce	Both consumers and manufacturers can choose to eliminate the production of waste by producing less.
R2 – Resell/reuse	transferring ownership of the asset to continue its life in its original function.
R3 - Repair	Bringing the asset back to working order. This is distinct from refurbishment as it can be smaller in scale and the intent is to reach the original performance not an ‘upgrade’.

Title	Description
R4 – Refurbish	The overall structure of a multi-component product remains intact while components are repaired or replaced. Usually the end result is a form of ‘upgrade’.
R5 – Remanufacture	Items are reused or components are adapted for another function. The material gets a distinct new life cycle.
R6 – Re-purpose	Items or components are adapted for another function. The material gets a distinct new life cycle.
R7 – Recycle materials	Re-use of the base resources to avoid the use of newly mined materials or resources. Recycling does not maintain any of the original product structure
R8 – Recover energy	Capturing the energy embodied in waste, including incineration in combination with producing energy or use of biomass.
R9 Re-mine	Retrieval of materials after landfilling (in the case of spacecraft, the equivalent is retrieval of materials in a graveyard orbit).
Cannibalisation	Selective retrieval of parts, typically focusing on the highest value parts.

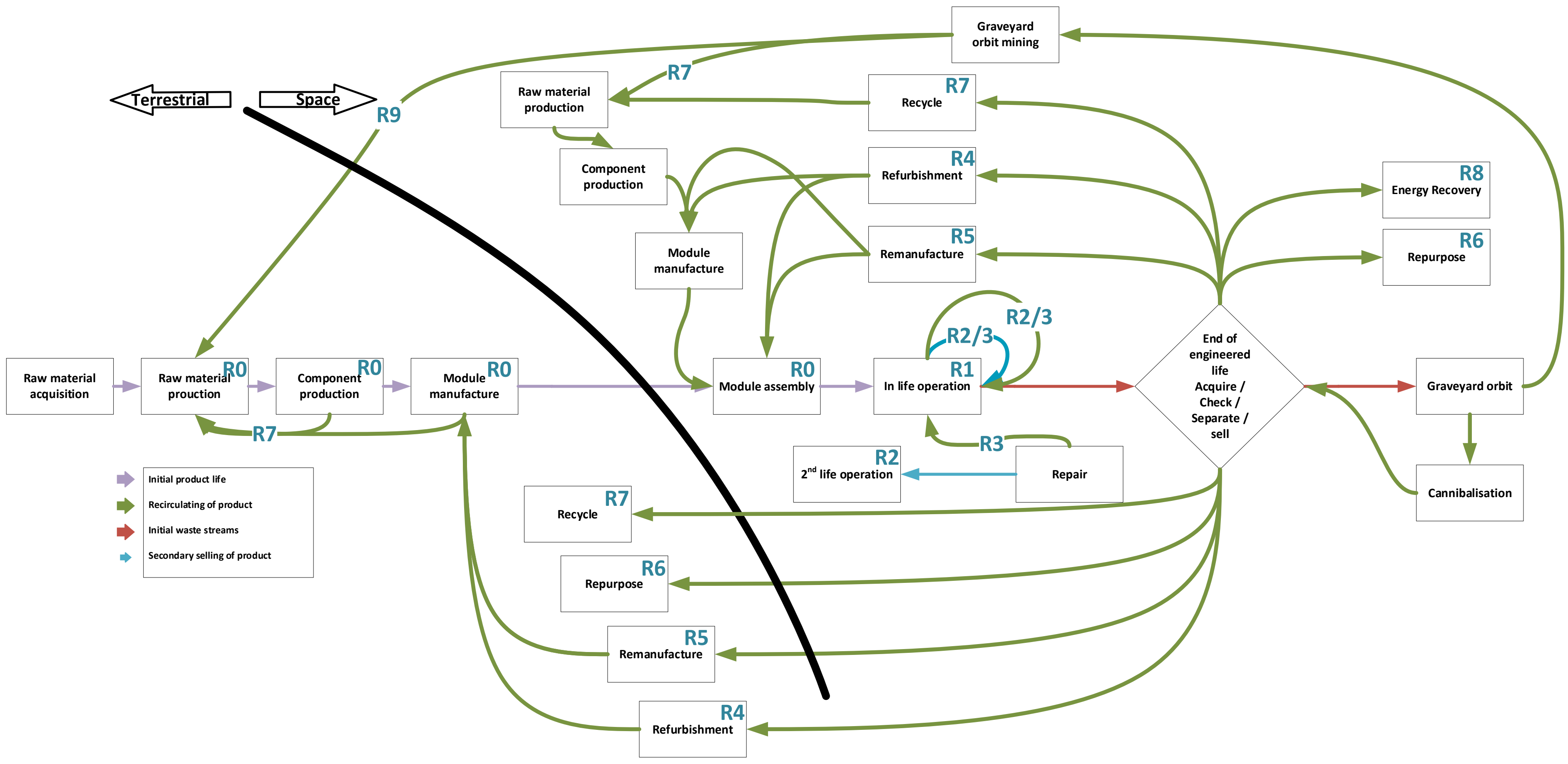

Figure 2 - Circular economy options

2.4 Work package 4 – Value Chain

This work package looked at the potential economic gain from applying the various 10R strategies to decommissioning components of an SPS. In order to do this a literature review was carried out to identify the possible end of life strategies which could be applied to various components including structural composites and Photo Voltaics (PV).

The value chain assessment identified that the technical options are likely to be the main drivers of value although supporting activities such as logistics, infrastructure and technology development will also play key roles in driving a commercially viable solution.

Whilst a number of potential 10R's strategies were looked for a variety of components, various recycling methods were identified for components terrestrially, no clear pre-existing pathways were identified for the development or use of these technologies in space. As such it is believed that a significant programme of future works would be required to progress these to a point where value could be extracted from a decommissioned SPS. The order of preference for 10R's strategies was identified to extract the maximum value from an SPS and reduce the potential environmental impact is shown in Figure 3.

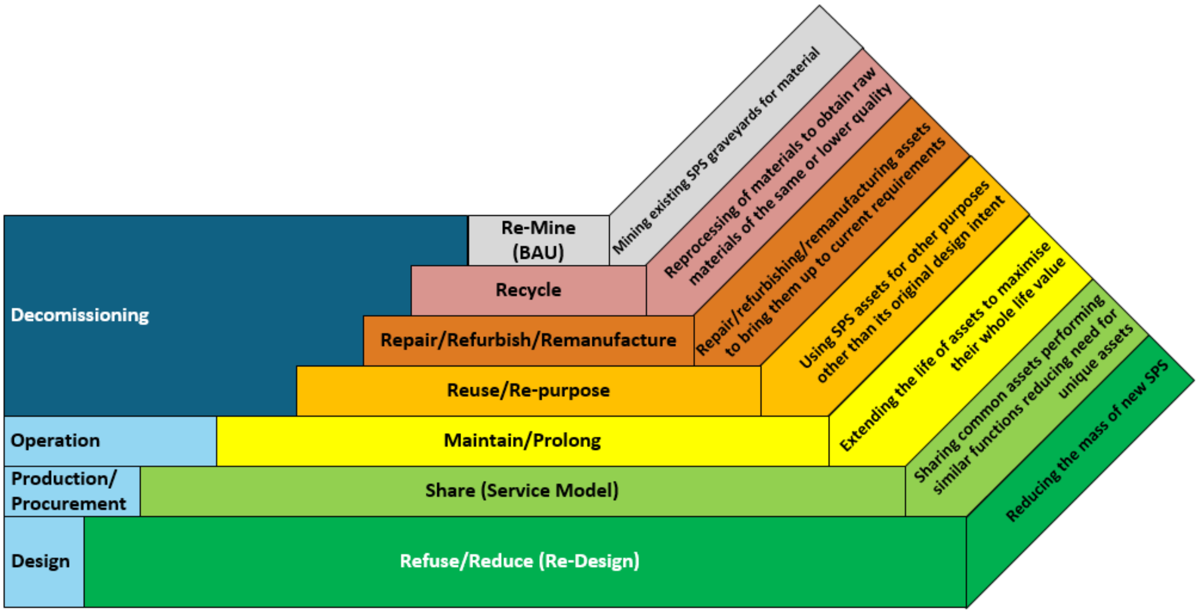

Figure 3 - 10R strategy order of preference

2.5 Work package 5 – Characteristics for sustainable decommissioning

This work package identified a number of characteristics and features of an SPS which designs will be able to use to enable a future SPS to be decommissioned in a sustainable manner. These characteristics reflect the need to balance cost, technical feasibility and environmental impact with through life performance. The key characteristics identified were modularity, designing for disassembly & maintenance, designing components to outlast the SPS life so as to be re-usable, limiting the complexity of the design and utilising purpose built components rather than COTS.

3 Conclusions

A characterisation of the current leading SPS designs is presented and broken down to a system level. This characterisation shows that many of the leading designs are still lacking key details and knowledge of basic design features such as material selection remain unknown. As such, a detailed breakdown and study of the viability of decommissioning a specific design cannot be conducted.

A framework is presented for assessing macro SPS decommissioning strategies as well as a discussion around the factors affecting individual 10R strategies. Discussion of the feasibility of several processes for applying these strategies to PV and structural components is also provided.

A number of macro strategies for decommissioning have been identified and discussed. Of these strategies most were deemed to be unlikely to be economically viable, technically challenging or result in waste or pollution to either the Earth or space environments.

SPS and, more generally, the future space economy presents a good opportunity for a local system to adopt circular economy principles and act as a demonstrator which could be extrapolated to Earth. The order of preference of circular economy strategies is dependent on which variable is being optimised for: economic benefit, limiting space junk or limiting environmental damage.

Current 10R strategies revolve around mechanical, chemical and thermal processes. Each have their own advantages and disadvantages. In the SPS time horizon there will likely be significant advances in each of these categories, although based on current knowledge and research the most likely to be used are those processes which provide life extension or allow components to be reused with minimal on orbit processing. In-orbit manufacturing is advancing rapidly but it appears that this may be limited to additive manufacturing of structural materials, rather than multistage complex chemical and thermal processes. For life extension techniques, a framework is required for assessing the trade-offs between: additional mass, development cost and benefit gained.

Decommissioning an SPS presents an opportunity to extract additional value form the SPS beyond its operational lifetime. The economics of SPS decommissioning will be determined by the inherent value of the material in space which will be a function of value gained from increasing commodity prices during its operational lifetime, the cost of launching new material and any value applied to the ability to prevent the vehicle from becoming space junk.

Comparatively, of the three types of feasible processing:

- Chemical processes are unlikely to be feasible for recycling and manufacturing on a large scale.
- Thermal processes will require significant advancements in thermal management and lead to significant mass and lifetime penalties.
- Mechanical processes may be possible but will require significant investment and advanced levels of automation.

The current and near-term outlook for recycling of existing structural materials in space is likely to focus on shredding materials and using them in future composites. Whilst it may be possible to recycle materials, turning these raw materials into useful components for future vehicles may be significantly more challenging. Therefore, reuse or limited repair of components is likely to be the preferred solution in the medium term. For the required timeframe In-orbit manufacturing is likely to be limited to 3D printing of beams and other structural elements. The approaches viability depends on the assembly speed, the total mass required to be launched and the overall cost.

The economics of decommissioning SPS will be driven by:

- the value of the material recovered and the cost of moving it to the required consumers
- the cost of turning this material into something useful
- the launch cost which determines the value inherent in the material from being at the top of a gravity well
- The value attributed to avoiding space junk or any potential environmental damage

If SBSP is to be successfully deployed in the future, having a sustainable method of decommissioning the SPS will be vital to ensuring its acceptance as a technology. SPS represent a step change in the mass of potential space junk and therefore dramatically increase the risk collision risk with other space user. There are opportunities in SBSP decommissioning which, if deployed correctly could be an exemplar for an Earth based circular economy.

There are no obvious, technically feasible, economically advantageous methods of sustainably decommissioning an SPS. Fundamental breakthroughs are required in a number of areas to allow SPS to be successfully and sustainably decommissioned. There are less sustainable methods which would allow an SPS to be decommissioned and may be feasible with current or nearer term technology. Whilst the challenges of developing sustainable decommissioning strategies are not insurmountable for humanity, they will require significant effort to solve and SBSP will need to be seen as a strategic or economic imperative. Ultimately, further study is required to assess the decommissioning potential of detailed SPS designs once these become available.

4 Recommendations

Based on the conclusions of this study the following recommendations are suggested for future work to explore sustainable decommissioning options for SBSP:

- This report has laid out an analysis pathway for assessing SBSP decommissioning options. However, the current leading SBSP designs are not sufficiently mature and do not exist in sufficient detail to carry out a comprehensive study. Future studies on SBSP decommissioning should be carried out progressively as the fidelity of SBSP design information matures.
- It is possible that regulation to enforce circular economy concepts and more scrutiny of the decommissioning of large assets will be a feature of future space industry operating environments, therefore studies to quantify the benefits and impacts of different options are recommended:
    - An environmental impact assessment of disposal by atmospheric burn up of SPS to understand the potential energy, carbon dioxide and other pollutant impacts of activities.
    - A ‘design-for-disposal’ strand of work to align the designs of SBSP (and other high value, high mass satellite concepts) with circular economy principles and sustainable characteristics core to the design.
- The availability of suitable graveyard orbits is necessary to enable some of the disposal solutions, further analysis is needed to assure these: in particular a detailed analysis of the likelihood of collisions between SPS in graveyard orbits.