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A PROCESS-BASED LIFE CYCLE SUSTAINABILITY ASSESSMENT OF THE SPACE-BASED SOLAR POWER CONCEPT

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Abstract

For space-based solar power (SBSP) to be considered as a truly viable renewable energy technology, there should be a clear environmental benefit gained from its application. Additionally, given the scale of investment and engineering development, the price of energy must remain comparable to terrestrial-based generation systems for commercial feasibility. For this reason, a process-based life cycle sustainability assessment (LCSA) study was conducted to identify the life cycle environmental, economic and social impacts of the 1978 DOE/NASA Solar Power Satellite (SPS) Reference System. This was one of the first ever LCSA studies for space systems to be performed worldwide and was applied using a new LCSA tool for space missions developed at the University of Strathclyde. Taking a burden-based approach, the tool has been used to calculate environmental impacts across a wide range of different environmental impact categories and quantify costs over the system life cycle. The inclusion of social impacts adds additional depth to the analysis by showcasing the sociological impacts of the system on various stakeholder groups in line with the 2030 Agenda for Sustainable Development. The calculated life cycle impacts were then analysed further to identify potential hotspots through multi-criteria decision analysis (MCDA) and by measuring the results against annual global impacts (AGIs) and planetary boundaries (PBs). Life cycle CO_2e emissions and costs were then compared to terrestrial energy generation systems in order to benchmark the relative performance of the technology as part of the conventional energy mix. The results suggest that whilst the DOE/NASA SPS Reference System can generally be described as a 'green' and 'cost-effective' system, several design improvements can and should be made to lessen its life cycle impacts. Therefore, it is proposed that the identified hotspots are used as a baseline for comparison or as mission drivers to continually improve future SPS designs.

Keywords: Space-Based Solar Power; Life Cycle Sustainability Assessment; Energy Systems; Comparative Analysis

Acronyms & Abbreviations

AGI Annual Global Impact
CDEP Concept Development & Evaluation Program
COTV Cargo Orbital Transfer Vehicle
DOE Department of Energy
EEIO Environmentally-Extended Input-Output
E-LCA Environmental Life Cycle Assessment
ESA European Space Agency
GEO Geosynchronous Earth Orbit
GHG Greenhouse Gas
HLLV Heavy Lift Launch Vehicle
IPCC Intergovernmental Panel on Climate Change
LCC Life Cycle Costing
LCI Life Cycle Inventory
LCIA Life Cycle Impact Assessment
LCOE Levelised Cost of Energy
LCSA Life Cycle Sustainability Assessment
LEO Low Earth Orbit
MAVT Multi-Attribute Value Theory
MCDA Multi-Criteria Decision Analysis
NASA National Aeronautics & Space Administration
NDC Nationally Determined Contribution
NPV Net Present Value
NREL National Renewable Energy Laboratory
PB Planetary Boundary
PLV Personnel Launch Vehicle
POTV Personnel Orbital Transfer Vehicle
PV Photovoltaic
R&D Research & Development
SBSP Space-Based Solar Power
SDG Sustainable Development Goal
SEIA Socio-Economic Impact Assessment
SETAC Society of Environmental Toxicology & Chemistry
S-LCA Social Life Cycle Assessment
SPS Solar Power Satellite
SSSD Strathclyde Space Systems Database
UNEP United Nations Environment Programme
WPT Wireless Power Transmission

1. Introduction

Since the 1970s, research into the space-based solar power (SBSP) concept has received considerable international attention as an alternative renewable energy source to conventional ground-based solar power. The basic theory proposes that a solar power satellite (SPS) be placed in orbit around Earth to capture sunlight. Using a series of photovoltaic (PV) arrays, the collected power is then converted into microwaves and wirelessly transmitted to Earth's surface at a frequency of 2.45 GHz or 5.8 GHz due to the attenuation of electromagnetic energy in Earth's atmosphere falling directly into the lowest range on these ISM bands. A rectifying antenna (or rectenna) on Earth's surface is then used to convert the beams into electricity and distribute it for use. Although these microwaves beams are well below ionising frequencies, a pilot signal emitted from the rectenna is used to keep the SPS aimed at the centre of the rectenna at all times. If this signal were to be interrupted for any reason, the microwave beam would automatically be defocussed or turned off [1].

Based on this concept, an SPS in geosynchronous Earth orbit (GEO) would be capable of generating power 24/7, except during the vernal and autumnal equinoxes where the system would move directly into the Earth's shadow for a maximum of 72 minutes at local midnight [2]. Accordingly, an extremely high capacity factor for the technology can be achieved, with recent findings suggesting that it could provide an average of 345% more power (W/m^2) than ground PVs with the same conversion efficiency, using current technologies [3]. This also takes into account wireless power transmission (WPT) losses with respect to the overall end-to-end efficiency of an SPS at system-level. Furthermore, the energy generated can also be directed to any of a variety of terrestrial locations on demand, which is particularly advantageous in the event of a natural disaster.

For these reasons, SBSP has traditionally been marketed as having great potential to assist in the fight against climate change and provide significant quantities of baseload power. As such, the envisioned goal of the concept is to help with the transition away from fossil fuels by providing a clean, affordable and continuous form of renewable energy which accords with current climate goals, taking into account the increasing demand for energy driven by a growing population. In this regard, one of the key selling points of the technology has traditionally been the fact that there are no conceivable emissions directly attributable to the utilisation phase since the system operates in outer space. However, such claims ignore the environmental impacts arising from other areas of the life cycle such as raw material extraction, production & manufacturing and launch. Additionally, no in-orbit demonstrations have ever taken place primarily due to the high initial upfront investment costs. This is mainly a consequence of the cost of access to space, which is currently around $2,719/kg USD at net present value (NPV) for a Falcon 9 launcher [4]. The risks involved with providing such substantial levels of funding for an unproven technology has meant that the SBSP concept has been stuck in a perpetual, vicious cycle for several decades with the concept struggling to get off the ground.

Therefore, in order to obtain the necessary levels of investment to break this cycle and potentially kick-start an entirely new industry, it is vital that the viability of the SBSP concept as a renewable energy option can be scientifically and quantifiably proven. For this reason, this paper presents the results of a process-based life cycle sustainability assessment (LCSA) study which was conducted to identify the life cycle environmental, economic and social impacts of the 1978 DOE/NASA SPS Reference System. The results of the analysis will then be explored further to identify potential hotspots in the system design. Life cycle CO_2e emissions and costs are then compared to terrestrial energy generation systems in order to benchmark the relative performance of the technology as part of the conventional energy mix. Consequently, the results of this analysis should act as impetus for continuous improvement of such systems and their future application.

2. Background & Literature Review

2.1 LCSA in the Context of Aerospace

LCSA is a new technique used to scientifically quantify and reduce adverse environmental, social and economic impacts of products, processes and services over their entire life cycle, based on the traditional 'three-pillar' interpretation of sustainability. However, rather than a model itself, LCSA is a framework of models designed to provide product-related information in the context of sustainability and allow integrated decision-making based on a life cycle perspective [5]. To achieve this, it combines environmental life cycle assessment (E-LCA), Social Life Cycle Assessment (S-LCA) and Life Cycle Costing (LCC) into a single framework as shown in Eq. 1 below:

$$LCSA = E\text{-}LCA + S\text{-}LCA + LCC \qquad \text{Eq. 1}$$

E-LCA is a tool used to assess environmental impacts of products over their entire life cycle from raw material extraction through processing & manufacturing, assembly, transportation, use and end of life [6,7]. S-LCA can be used to predict the social and sociological aspects of products whilst LCC can be used to determine the entire cost of a product, process or service over its entire life cycle including both one time and recurring costs [8,9].

However, applying LCSA to space systems is not straightforward since conventional life cycle databases and tools typically consist of common, mass-produced products and processes which make them virtually incapable of accounting for the complexities of the space industry. Space technologies have low production rates, long development cycles and use specialised materials and industrial processes with an extremely high cost per weight ratio. These components also have to satisfy stringent safety and quality requirements which means that they are subjected to significantly more research and testing than other projects. Additionally, monetary flows are vastly different than in other sectors as the industry does not fulfil the requirements of a completely free market due to state financing schemes and limited players, which adds further complexity [10,11].

To address this, a space-specific LCSA framework has recently been developed, including a new LCSA database called the Strathclyde Space Systems Database (SSSD) which can be integrated into the concurrent design process of space missions to identify design hotspots and improve their sustainability performance. An overview of this framework is presented in Figure 1 below and will be described further in Section 3.1 in relation to how it is implemented through the SSSD.

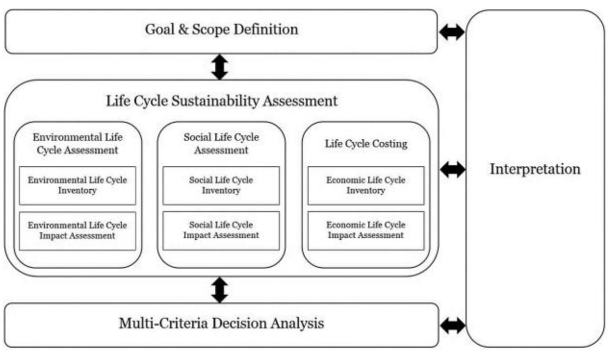

Figure 1: The proposed space-specific framework [10]

2.2 System Description

The DOE/NASA SPS Reference System was a result of early interest in SBSP following the patent of the SPS concept in 1973 [12]. In 1976, the Department of Energy (DOE) initiated a multi-year study programme in cooperation with the National Aeronautics & Space Administration (NASA) which intended to evaluate the potential of SBSP. Supported by NASA, the DOE's Concept Development and Evaluation Program (CDEP) [13] was funded at a level of approximately $20 million in 1978 USD [1]. The emphasis of this programme was on implementation of SPS systems rather than framing strategic research and development (R&D) goals or initial demonstrations. As a result, the DOE/NASA SPS Reference System concept was put forward. However, government-sponsored SPS activities were terminated in the United States in the 1980's following unfavourable reviews by the Congressional Office of Technology Assessment and the National Research Council based on the near-term feasibility of the system concept and the monumental cost estimates [1]. Despite this, the system remains as one of the most detailed SPS system concepts ever produced and one of the most representative plans of a future SPS system.

The configuration of DOE/NASA SPS Reference System is illustrated in Figure 2 and consists of a solar array structure built from a graphite composite material. Two conversion options were considered in the CDEP [13]. The first exploits single-crystal silicon solar cells whilst the other option utilises single-crystal gallium-aluminium-arsenide solar cells with a concentration ratio of 2. Each option is sized for 5 GW DC power output into a conventional power grid. The overall efficiency has been calculated for a worst-case scenario which is approximately 6.79% for the silicon option and 7.06% for the gallium arsenide option. This means that it is necessary to size the solar arrays to intercept slightly more than 70 GW of solar energy. Overall, the complete system comprises of 60 units, which creates a total capacity of 300 GW. This means that the scheme as a whole would become the single largest power system in the world, far surpassing the Three Gorges Dam which has an installed generating capacity of 22.5 GW [14].

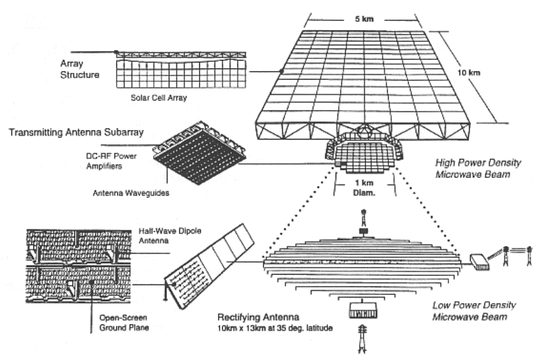

Figure 2: The 1978 DOE/NASA SPS Reference System [12]

As can be seen from Figure 2, the SPS unit itself has a rectangular structure 10 km long by 5 km wide and 300 meters deep and carries sun-pointing PV panels over its surface. An end-mounted antenna of 1 km in diameter is used to transmit the power generated to the rectenna on Earth via microwaves using an operating frequency of 2.45 GHz. According to the CDEP [13], each satellite will be placed in GEO with 0° inclination and eccentricity (i.e. geostationary) at an altitude of 35,800 km due to its near uninterrupted transmission potential, low antenna steering accelerations and to keep the platform stationary with respect to the rectenna locations on Earth. The rectennas themselves are in the shape of an ellipse (13km by 10km) and have the ability to receive and rectify the microwave beam. The system has been designed to ensure that the peak microwave power density will not exceed 23 mW/cm^2 at the centre of the rectenna and 1 mW/cm^2 at the edge of the rectenna in order to comply with national safety limits for human electromagnetic exposure. It is theorised that each of the rectennas required for the DOE/NASA SPS Reference System would run coast-to-coast along the 34° latitude line.

Assuming a rate of implementation of two SPS units per year [13], Figure 3 shows the expected energy output of the system, which has been calculated on an annual basis from 2040 to 2100, including leap years. It also considers interruption to power generation during the vernal and autumnal equinoxes (for a total annual eclipse period of ~82.44 hours) as well as for maintenance procedures (power losses assumed at ~1% per year). Taking all this into account, the system is capable of generating a total of 77,388.9336 TWh over its operational life span. This gives the system a capacity factor of 98.09%.

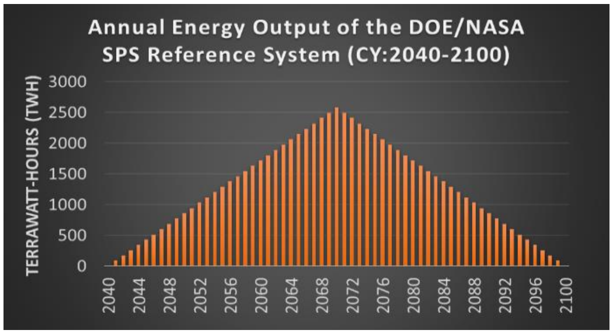

Figure 3: Annual Energy Output of the DOE/NASA SPS Reference System (CY:2040-2100)

For comparison, direct primary energy consumption in 2019 was 14,421 Mtoe globally [15] and 2,524 Mtoe in the United States [16]. Since the calculated energy output of the DOE/NASA SPS Reference System is 2.58 million GWh per year on average, this means that the system is capable of providing about 1.54% of global energy demand and about 8.79% of the energy demand of the United States relative to 2019 levels.

2.3 Previous Sustainability Studies

Despite the perceived environmental benefits of SBSP, only one previous E-LCA study has ever taken place for the technology. Conducted by Asakura et al. [17] in 2000 (which was expanded on in 2005 by Hayami et al. [18]), this analysis attempted to quantify the life cycle CO_2 emissions of the DOE/NASA SPS Reference System. The calculation covered the production of rocket fuel and solar panels as well as the construction of the rectenna, satellite and all equipment listed in the DOE/NASA SPS Reference System, including the space bases and transportation vehicles. From this, the results suggest that the CO_2 emissions produced by the system per unit of energy generated would be around 20 gCO_2/kWh. This value falls to about 11 gCO_2/kWh through a breeder scenario where each installed SPS supplies the electricity required for producing further SPS units. They conclude by stating that the baseline scenario is comparable to nuclear power systems at 22 gCO_2/kWh. However, the main drawback of this analysis is that the methodology adopted was an Environmentally-Extended Input Output (EEIO) model which focused exclusively on CO_2 using 1990 Japanese input-output tables, broken down into 405 sectors. EEIO models quantify environmental impacts that are directly attributable to specific sectors of the economy based on purchases made between other sectors to produce its final output. It is not a wholly precise method of analysis as it cannot distinguish between products of different monetary values within a single sector [19]. Given that monetary flows in the space industry are vastly different than in other sectors (as detailed in Section 2.1), the European Space Agency (ESA) do not recommend applying EEIO databases to space-specific E-LCAs since they produce a highly inaccurate measure of environmental impacts [11]. This has meant that there has been no scientific evidence robust enough to support such an environmental claim or indeed justify any kind of environmental declaration of the SBSP concept to date.

In terms of LCC, several cost estimates have been attempted. Of particular relevance is the 1981 cost estimate of the DOE/NASA SPS Reference System [20] which covered five programme phases which were R&D, engineering verification, demonstration, investment, and production. Overall, this resulted in an average unit cost of $2,260/kW in 1977 USD, based on an estimated programme cost of $102 billion through the first operational unit, with subsequent units estimated to cost $11.27 billion each. This is the equivalent to around $9,693/kW at NPV. The breakdown of the original cost per unit consists of the SPS construction cost ($5 billion), space transportation cost ($2.8 billion), rectenna cost ($2.2 billion), assembly & support cost during construction of the space bases ($840 million), and programme management & integration costs including maintenance ($430 million). All of these costs refer to an SPS system which uses silicon solar cells. Costs for a system which use gallium arsenide are similar despite the higher solar cell costs, due to the lower mass required per unit which vastly reduces space transportation cost. As an estimate, the study predicts the total cost per unit to be around $13.80 billion USD (although this figure is not directly comparable to the silicon option due to slight differences in the applied cost-estimating methodology). However, Zubrin argues against the cost effectiveness of the SBSP concept based on its current technology capabilities in comparison to conventional energy generation systems, estimating that the total cost to deliver an entire SPS could be up to $6 trillion USD [21].

In contrast, a space-related S-LCA has never taken place in relation to the SBSP concept due to the novelty of the approach, whilst no socio-economic impact assessment (SEIA) on the topic could be found. As such, social impacts have generally not been considered beyond conducting talks with a small number of public interest groups and professional societies on issues such as environmental & health risks, land-use, military implications and costs or through short qualitative narratives in relation to the predicted social benefits of implementing the technology [1,22].

3. Materials & Methods

3.1 The Strathclyde Space Systems Database

The LCSA will be conducted using the SSSD which a new process-based tool developed at the University of Strathclyde to determine the life cycle sustainability impacts of space systems. Validated at ESA through a collaborative project in late 2018 [23], the SSSD has already been used in the design of several space missions [24,25,26]. It consists of 250 unique space-specific life cycle sustainability datasets, based on Ecoinvent and ELCD background inventories, which each contain environmental, costing and social data. The SSSD also includes several impact categories at midpoint-level. This is a problem-oriented approach which quantifies and translates the life cycle impacts into themes such as climate change, ozone depletion, acidification, human toxicity, social performance, costs, etc. Additionally, the SSSD is based on the space-specific LCSA framework presented in Figure 1 which allows the tool to align closely with widely accepted international standards and norms. An overview of these principles can be seen in Table 1 below, which have been used within the framework to form a coordinated, overarching approach for integrating each sustainability dimension within a single assessment.

Table 1: Space LCSA framework guiding principles [10]

Assessment Type	Guiding Documents
E-LCA	• ESA LCA Space System Guidelines • ISO 14040:2006 • ISO 4044:2006 • Product Environment Footprint Category Rules Guidance
S-LCA	• A/RES/70/1 • A/RES/71/313 • Global Reporting Initiative • Handbook for Product Social Impact Assessment • ISO 26000:2010 • UN Global Compact Framework • UNEP/SETAC S-LCA Guidelines • World Resources Institute
LCC	• IEC 60300-3-3:2017 • NASA Cost Estimating Handbook
LCSA	• UNEP/SETAC Guidelines for LCA Databases • UNEP/SETAC LCSA Guidelines

The purpose of the tool is to quantitatively and scientifically sustainability hotspots in the space mission design process during concurrent design activities, and use this information to lower adverse environmental, social and economic impacts. This is achieved through a process-based methodology which relies on physical activity data to develop a product tree derived from assessing all the known inputs of a particular process and calculating the direct impacts associated with the outputs of that process.

In addition to this, the inclusion of multi-criteria decision analysis (MCDA) within the framework allows criticality of each sustainability dimension to be determined. As can be seen in Figure 4 below, the approach generates a single relative score which can then be fed back into back into the concurrent design process. Although it could be argued that this approach is less scientific because it adds an element of subjectivity to the analysis, it simplifies the decision-making process, thereby reducing the learning curve for other engineers. When applied within the CE process, it is referred to as life cycle engineering which is a technique used to find a balance between technical considerations, societal needs, economic concerns and minimising environmental impacts in product design [27]. This allows the space mission design to be reiterated based on the hotspots identified across each sustainability dimension according to their contribution to the total single score. As such, the application of the MCDA approach within this analysis is useful as a potential method for hotspot identification.

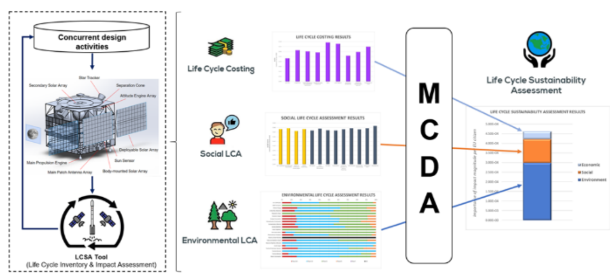

Figure 4: System boundary of compared energy technologies

A full methodological description of the SSSD is provided within [10], whilst a description of the life cycle impact assessment (LCIA) and MCDA calculation procedures are provided in Section 4.2.

3.2 Benchmarking Sources

The baseline findings and MCDA results produced by the SSSD can also be compared against interpretable norms in order to benchmark the relative performance of the DOE/NASA SPS Reference System. For this reason, annual global impacts (AGIs) and planetary boundaries (PBs) have been used to define this. AGIs refer to the pressure place on the planet by the sum of all anthropogenic activities over a predefined calendar year.

PBs refer to the world's ecological threshold whereby it can continue to safely operate to maintain a sustainable human presence on Earth. The European Commission's Joint Research Centre provides a set of values for each of these [28,29], which will be applied within this analysis. Additionally, previous research by the lead author of this study proposed new values for social and economic life cycle impacts which have also been incorporated [10].

Comparison to other energy generation technologies have been made based on averaged OpenEI data [30,31]. This is relevant for a total of eight renewable technologies and three fossil fuel technologies for both CO_2e emissions and costs. In this regard, CO_2e emissions are measured in gCO_2e/kWh whilst costs have been calculated in terms of historical and projected levelized cost of energy (LCOE), measured in USD/kWh, to the value of the dollar in 2015. More specifically, with funding from DOE, the National Renewable Energy Laboratory (NREL) initiated the 'LCA Harmonization Project' in an effort to rigorously leverage the numerous individual E-LCA studies to develop collective insights into the amount of CO_2e/kWh of different energy generation systems [32]. Harmonisation is a meta-analytical procedure which was applied to adjust the estimates so that they accord with the same system boundary (as presented in Figure 5) in order to be methodologically more consistent and therefore more comparable. Cost data is based on the same system boundary, which is comparable to (although less detailed than) the system boundary adopted by this study, as can be seen in Figure 6). It uses DOE Programme Estimates and NREL Annual Technology Baseline data which provides a consistent set of technology cost and performance parameters for energy analysis [33].

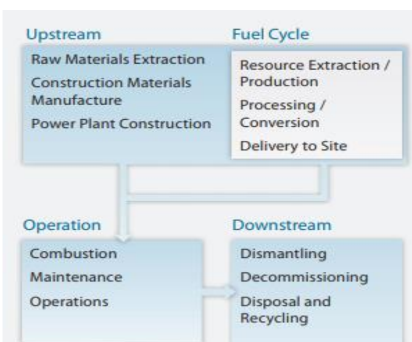

Figure 5: System boundary of compared terrestrial-based energy generation technologies [34]

The total estimate count across all terrestrial-based energy generation technologies are provided in Table 2 for life cycle CO_2e emissions and LCOE values. The range of estimates are relevant for the period of 1970-2010 for CO_2e emissions. In comparison, the LCOE estimates also take future predicted costs into account, and is therefore relevant for the period of 2004-2054.

Table 2: Count of estimates per energy source [30,31]

Energy Source	Count of Estimates: Life Cycle GHG Emissions (1970-2010)	Count of Estimates: Historical & Projected LCOE (2004-2054)
Bio-Power	222	604
Coal	169	714
Concentrated PV	42	597
Geothermal	8	413
Hydropower	28	59
Natural Gas	83	504
Nuclear	125	197
Ocean	10	5
Oil	24	77
PV	124	527
Wind	126	862

3.3 Study Limitations

It is important that the limitations of this analysis are outlined in order to identify potential weaknesses of the study. Firstly, the analysis is only capable of providing generic system-level results since highly detailed subsystem data could not be obtained from the CDEP documents for the purposes of this study. This meant that a life cycle inventory (LCI) with sufficient detail beyond system-level could not be formed. Additionally, the SSSD used to compile the LCI has a mainly European focus. Although the provider of most datasets could be altered using a vertical-horizontal aggregation approach, these could not always be specifically tailored to the United States with respect to the DOE/NASA SPS Reference System. In such cases, a global perspective was used where possible. Another issue with the SSSD is that prior to the study, it did not contain a complete set of datasets which would specifically be required to model the full DOE/NASA SPS Reference System. To rectify this, new datasets were implemented where possible based on literature reviews. However, some datasets had to forcibly be represented through proxies or comparable alternatives. With regard to the social impacts, only the stakeholder categories of value chain actors and workers are currently modelled due to a lack of data within the social LCI of the SSSD stemming from a lack of willingness from organisations to contribute data. As such, the risk values of each stakeholder category have been altered to reflect this. Finally, the normalisation & weighting factors and AGIs & PBs are not currently available for all impact categories, meaning that potentially meaningful impacts may get overlooked as part of the analysis. The affected impact categories are CRMDP, TCED, IRP, PMFP, FRDP, HTP and METP (see Table 5). Further analysis may be required to determine the extent of this exclusion and the potential significance of the impacts related to each of them. This is because they are yet to be defined by AGIs and/or PBs from a life cycle perspective.

3.4 Disclosure Statement

For complete transparency and disclosure purposes, it should be noted that the funding of this analysis was provided by SPACE Canada, who are a not-for-profit organisation dedicated to the promotion of SBSP. Their mandate is to support, encourage and facilitate international dialogue on SBSP through education, research and commercialisation. Additionally, they also part-funded the development of the SSSD (along with the Engineering and Physical Sciences Research Council). This was to facilitate this analysis in order to address and/or support the currently precarious green marketing claims surrounding SBSP and potentially justify funding for future SPS missions. For this reason, despite the potential vested interest and motivations of the funder, the principal investigator of this study (the corresponding author of this paper), ensured that academic vigour and integrity was maintained throughout the study and that the analysis was grounded in scientific and factual principles to the furthest extent possible, based on the current state of knowledge.

4. Theory & Calculation

4.1 Goal, Scope and Inventory Information

According to the space-specific LCSA framework outlined in Section 2.1, a combined goal and scope definition should be outlined. In this regard, the goal of this study is to quantitatively and scientifically evaluate the life cycle sustainability impacts of the DOE/NASA SPS Reference System, with a view to identifying any potential design hotspots, before benchmarking the life cycle CO_2e emissions and costs to terrestrial energy technologies. The reason that this comparison will only take into account CO_2e emissions and costs is that these two elements are the main drivers affecting the feasibility of the SBSP concept.

The LCI was formed based on the system boundary outlined in Figure 6. The information and data used to populate the LCI was mainly based on the NASA CDEP Reference System Report [13] and Preliminary Materials Assessment Report [35] along with other associated documents. Overall, the DOE/NASA SPS Reference System concept applied a system margin of 25% to all stated values which is therefore reflected in the environmental, social and economic impacts. Some of the main points and assumptions used within this analysis will now be outlined for complete transparency.

According to the CDEP Report [13], it would take 6 months to construct a base in low Earth orbit (LEO) and 9 months to construct GEO base. A total crew size of 715 would be required for construction of the bases (680 in GEO and 35 in LEO). Using the mass statement and materials list for the DOE/NASA SPS Reference System concept outlined for the DOE/NASA SPS Reference System, under the silicon option, the LEO base would have a total mass of 2,405 MT whilst the GEO base would be 8,353 MT. For the gallium arsenide option, the mass of the LEO base was assumed to be 1,832 MT whilst the GEO base was 6,000 MT.

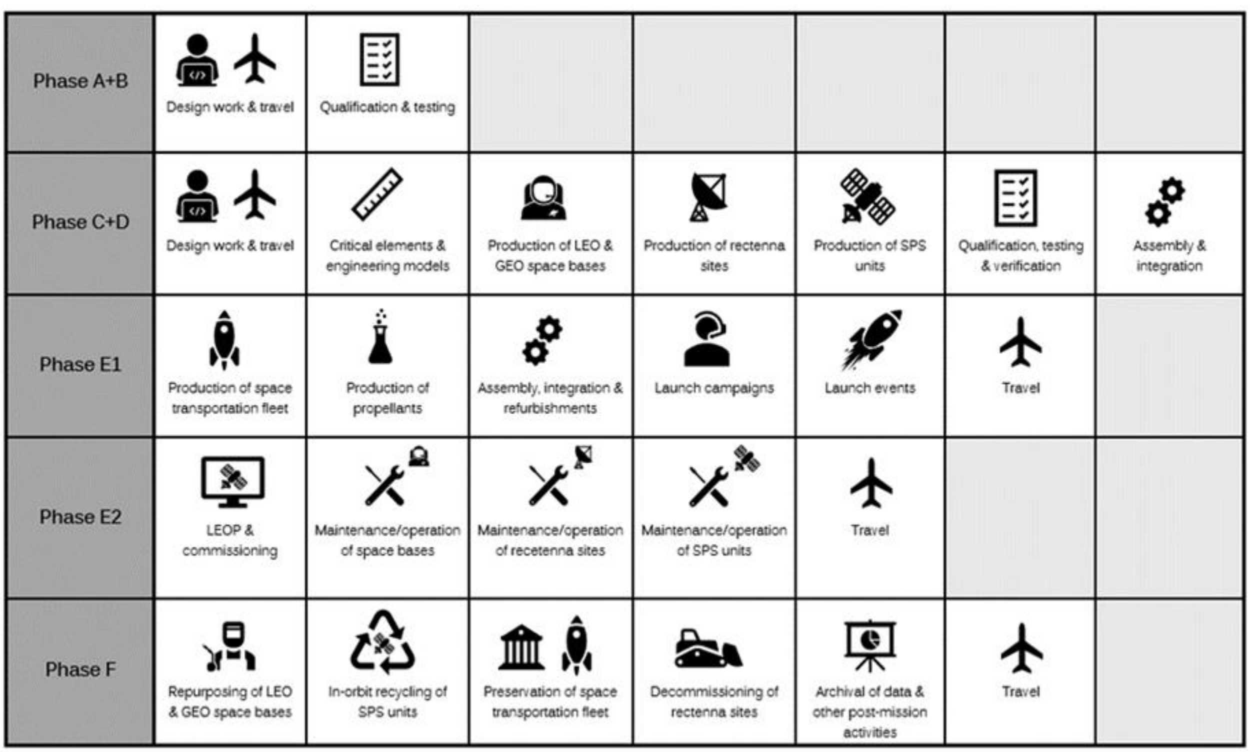

Figure 6: System boundary applied to the DOE/NASA SPS Reference System

Each SPS takes 6 months to construct using a crew of 480 in GEO and a crew of 75 in LEO. The system lifetime of each SPS is 30 years, with the rate of implementation expected to be two units per year over the 2040 to 2070 period. All of the materials for construction have been derived from Earth resources and manufactured into launch-ready components. The technology availability has been modelled up to the present day. Using the CDEP mass statement and materials list, the total mass of the each SPS unit is 50,618 MT for the silicon option and 34,159 MT for the gallium arsenide option. Propellant requirements of each unit (oxygen, hydrogen, argon) are also included [13,35,36,].

The rectenna construction is estimated to last about 15 months per rectenna, using a total crew of 9,272 for 24/7 operation based on shift size of 2,474 workers. The total mass of each rectenna is 1,765,009 MT which consists of 1,492,000 MT of steel, 1,330,000 MT of concrete and 140,000 MT of aluminium [13,35]. The construction was modelled based on nine major activities which are site survey engineering & land acquisition, support facilities installation, reference coordinates, site clearing, panel pad grading, panel installation operations, 40 kVac bus installation, converter station installation and 500 kVac bus installation [37].

In terms of the space transportation system, four vehicles used for all programme operations. These are the Heavy Lift Launch Vehicle (HLLV), the Personnel Launch Vehicle (PLV), the Cargo Orbital Transfer Vehicle (COTV) the Personnel Orbital Transfer Vehicle (POTV). The specifications of each of these vehicles are outlined below [13].

- **HLLV:** a two-staged, vertical launch, winged, horizontal landing reusable vehicle capable of transporting a payload of 424 MT payload to LEO. It has an empty mass of 1,170 MT uses LOX/LH_2 and LOX/CH_4 propellant.
- **PLV:** a modified space shuttle orbiter with a passenger module with an empty mass of 264 MT. The two-stage reusable vehicle is for transporting personnel to LEO, using LOX/LH_2 and LOX/CH_4 propellant.
- **POTV:** a two-stage reusable, chemical fuel vehicle which is for transferring personnel from LEO to GEO and return to LEO. It has an empty mass of 116 MT and uses LOX/LH_2 and Argon.
- **COTV**: an independent, reusable electric engine-powered vehicle for transporting cargo from the HLLV delivery site in LEO to GEO. It is powered by silicon or gallium arsenide solar cells leading to an empty mass of 1,100 MT for the silicon option and 679 MT for the gallium arsenide option. However, despite being mostly electrically powered, small quantities of LOX/LH_2 and Argon are also used.

For all HLLV and PLV launches, Kennedy Space Center was selected as the Earth launch site. The expected lifetime is around 300 flights for HLLV, 100 flights for PLV and POTV and 20 flights for COTV [38]. Tables 3 and 4 below outlined the space transportation requirements to construct the LEO and GEO space bases and the SPS units, assuming a zero launch failure rate.

Table 3: Space transportation requirements for LEO & GEO space base construction [13,38]

LEO & GEO base construction				
Vehicle	**Number of flights**		**Fleet size**	
	Si	**Ga**	**Si**	**Ga**
HLLV	118	110	5	3
PLV	32	31	2	2
COTV	3	2	23	9
POTV	6	8	2	1

Table 4: Space transportation requirements for the installation of two 5GW SPS units per year [13,38]

Two 5GW SPS units per year				
Vehicle	**Number of flights**		**Fleet size**	
	Si	**Ga**	**Si**	**Ga**
HLLV	375	225	5	3
PLV	30	38	2	2
COTV	30	22	23	9
POTV	12	17	2	1

Maintenance and operation procedures take place over the 2040 to 2100 period, assuming ~1% replacement rate per year for both the SPS units and rectenna components [39]. Heating effects from the WPT are not considered within this analysis due to difficulties in quantifying this effect in terms of CO_2e. With respect to global warming, this aspect is considered to be insignificant [40], with current estimates predicting that the heating generated would be on the order of around 0.006˚C for several thousand SPSs with an installed capacity of 15,000 GW [1]. Additionally, each operational SPS has a crew size of 30 at GEO for maintenance and 24 at LEO. Crews which have completed their 90-day GEO duty cycle are transported to LEO by returning POTV's. The crew module with its crew and the two spent stages are then returned to Earth via HLLV's [13]. Therefore, if operations and maintenance continue for 30 years after the last SPS is constructed, then this means that between 2070 and 2100 a total of 610 HLLV and 244 POTV trips will be made for the Si option whilst 366 HLLV and 122 POTV will be made for the Ga option. Therefore, an additional 3 HLLVs and 3 POTVs will be required for the Si option and an additional 2 HLLVs and 2 POTVs will be required for the Ga option over this time period at a minimum.

No end-of-life scenario is provided for by the CDEP [13] as the system does not factor in salvage value or disposition costs at end of life. As such, this is the only part of the analysis where the applied system boundary deviates from the stated scenario of the CDEP. It is assumed that the rectennas will be completely decommissioned, with the land returned to a natural state. In terms of the SPS units, no resources will be returned to Earth. Instead, they are collected and recycled in-orbit for reuse on the moon (in a separate mission assuming a lunar base has been established). However, the contribution of space transportation from Earth to collect this material and its ecospheric impacts have been considered, in part with launches from the moon. It is also envisioned that all space transportation vehicles will not be decommissioned at the end of life, and instead will be preserved where possible. This is because the DOE/NASA SPS Reference System has the potential to start up an entirely new industry, meaning that the programme can be considered as of historical importance. As such, the vehicle fleets will be put into museums, in a similar manner to the Space Shuttle Orbiters [41].

4.2 Impact Assessment Procedures

The LCIA results can be calculated by converting LCI results into common units using characterisation factors [6,7]. These are applied to each individual intervention classified as part of a given impact category in order to determine its relative contribution based on its fate, exposure and effect. The converted units are then aggregated within the same impact category to arrive at a numerical indicator result. As such, based on the IPAT equation, midpoint impact category results are typically calculated by:

$$IR_i = \sum_s CF_{is} \cdot m_s \qquad \text{Eq. 2}$$

where IR_i is the indicator result for impact category i, CF_{is} is the characterisation factor that connects intervention s with impact category i, and m_s is the size of intervention s.

The selected impact categories used as part of this analysis reflect a variety of different midpoint indicators used by the SSSD, based on those recommended by the International Reference Life Cycle Data System [42]. An overview of these can be seen in Table 5 below. This also includes some new impact categories, including social performance and costs. In particular, a burden-based approach for social performance at organisational-level was developed using a number of custom-made social indicators. These were developed to align with the Sustainable Development Goals (SDGs) using a similar scoring mechanism to the SDG Index [43], quantified in terms of man-hours. Costs are based on a parametric-analogous hybrid, activity-based costing methodology, which takes into account exchange and discount rates to convert costs into NPV for a given currency. Both indicators can also act as complete/independent analyses.

Table 5: Study Impact Categories

Impact Category	**Abbreviation**	**Method**
Air Acidification	AAP	CML
Global Warming	GWP	IPCC
Critical Raw Materials Use	CRMDP	SSSD
Economic Cost Impact	ECIP	SSSD
Total Cumulative Energy Demand	TCED	CED
Freshwater Eutrophication	FEP	ReCiPe
Marine Eutrophication	MEP	ReCiPe
Ionising Radiation	IRP	ReCiPe
Ozone Depletion	ODP	CML
Particulate Matter Formation	PMFP	ReCiPe
Photochemical Oxidation	POP	ReCiPe
Fossil Resource Depletion	FRDP	CML
Mineral Resource Depletion	MRDP	CML
Organisational Social Performance	OSP	SSSD
Freshwater Aquatic Ecotoxicity	FAETP	USEtox
Human Toxicity	HTP	USEtox
Marine Ecotoxicity	METP	CML
Water Depletion	WDP	ReCiPe

When interpreting trade-offs between these impact categories to identify hotspots, a systematic and structured decision-analysis technique is required. In this regard, MCDA can be applied to address problems with conflicting goals, handle diverse forms of data and reach conclusions, particularly when there could be multiple perspectives as with sustainability issues [44]. As documented by Velasquez & Hester [45], various methodological approaches exist for MCDA, but of particular relevance to LCSA is the multi-attribute value theory (MAVT) approach [46]. This quantitatively compares a set of attributes or criteria by calculating their performance with respect to a given objective. In this respect, the MAVT approach can be used to assign real numbers to different alternatives in order to produce a preference order on the alternatives consistent with decision-maker value judgements [47]. The technique is particularly useful when assessing trade-offs between conflicting criteria, combining dissimilar measurement units or identifying hotspots by their relative contribution. The MAVT approach is typically based on the following weighted sum formula:

$$v(a) = \sum_{i=1}^{I} w_i \cdot v_i(a) \qquad \text{Eq. 3}$$

where $v(a)$ is the overall sustainability score of product a, w_i is the weighting factor for impact category i, $v_i(a)$ is the score reflecting performance of product a, and I is the total number of impact categories.

In this regard, $v_i(a)$ can be calculated for all environmental impact categories through normalisation procedures, whereby the LCIA results are benchmarked against average European consumption levels defined by the Joint Research Centre [48]. This is then multiplied by a meta-weighting factor also defined by the Joint Research Centre which outlines the relative importance of a given impact category (i.e. the severity of the threat) from a European perspective [49]. The sum of all weighted values should therefore equal one. Since social performance and costs are not included as part of this, these have been further defined as part of this analysis. For social performance, the normalisation value is based on the annual hours worked per employee in the OECD (1,734 hours) whilst costs refer to the amount of money an average European spends on space activities (€7.34 in CY:2000) [50,51]. Since these impact categories are sustainability dimensions in their own right, their weighting value is equal to one. Finally, w_i reflects the importance of each sustainability dimension based on the most dominant political framework for sustainability currently in existence. In this regard, the number of indicators contained within the 2030 Agenda for Sustainable Development [52] has been used to provide a reasonable assumption concerning the current internationally accepted level of concern for each dimension. This approach has therefore been used to provide weighting factors for each sustainability dimension, as exemplified in [10].

5. Results & Analysis

5.1 Baseline Findings

The calculated LCIA results are relevant for both the silicon and gallium arsenide options of the DOE/NASA SPS Reference System over the entire lifespan of the programme. These are presented within Table 6 below.

Table 6: LCIA results for the silicon and gallium arsenide options of the DOE/NASA SPS Reference System

Impact Category	Reference Unit	LCIA Result	
		Si Option	Ga Option
AAP	kg SO_2 eq.	4.95E+10	5.11E+10
GWP	kg CO_2 eq.	8.69E+12	9.49E+12
CRMDP	kg mass	7.70E+09	1.34E+10
ECIP	EUR 2000	2.27E+12	2.27E+12
TCED	MJ	1.36E+14	1.50E+14
FEP	kg P eq.	4.38E+09	5.64E+09
MEP	kg N eq.	9.42E+09	9.97E+09
IRP	kg U^{235} eq.	1.53E+12	1.95E+12
ODP	kg CFC-11 eq.	2.32E+10	1.45E+10
PMFP	kg PM_{10} eq.	2.26E+10	2.82E+10
POP	kg NMVOC	2.87E+10	2.97E+10
FRDP	MJ fossil	9.60E+13	1.05E+14
MRDP	kg Sb eq.	1.38E+09	2.78E+13
OSP	Social Score	2.38E+12	9.52E+11
FAETP	PAF.m^3.day	9.94E+13	9.27E+14
HTP	cases	9.99E+06	2.04E+11
METP	kg 1,4-db eq.	2.17E+16	2.11E+18
WDP	m^3	5.68E+13	5.07E+13

Figures 7 and 8 below present an overview as to the where in the life cycle that these impacts occur. The baseline findings suggest that most of the life cycle impacts were driven by the rectenna production and decommissioning during Phases C+D and F, indicating that it could be a design hotspot. The reason for this is primarily due to the scale of operations given that the total area of land required for the 60 rectennas would be approximately 6,126 km^2 [13].

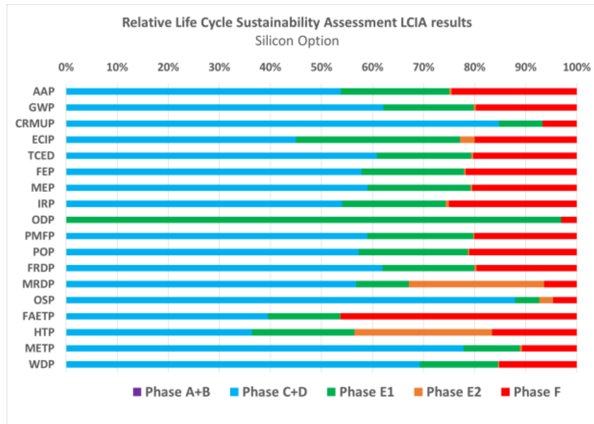

Figure 7: Relative LCIA results of the silicon option

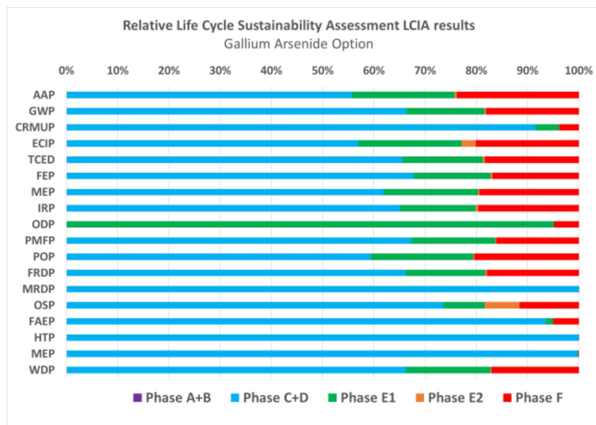

Figure 8: Relative LCIA results of the gallium arsenide option

Additionally, Figure 9 below provides an overview of the differences in LCIA results between each SPS option across all of the impact categories. From this, it can be seen that the major differences in LCIA results (over 60%) related to MRDP and all of the toxicity impact categories. The was due to the use of germanium as a substrate in the gallium arsenide solar cells given the scarcity of the material as a resource and the arsenic, dioxins and mercury released as part of its manufacturing process. This finding may also suggest that germanium could be considered a design hotspot of the gallium arsenide option. Additionally, OSP was also vastly more impactful for the silicon option due to greater SPS manufacturing times required.

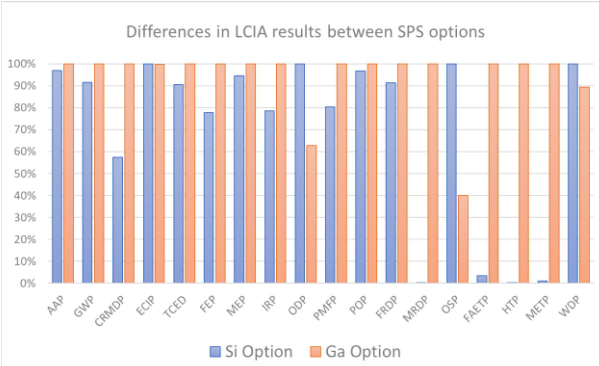

Figure 9: Differences in life cycle sustainability assessment LCIA results between SPS options

5.2 MCDA Results

Although the baseline findings can be viewed as standalone results, to gauge the relative criticality of each sustainability dimension, MCDA was applied using the MAVT method. The output of this for both options can be seen in Figure 10 below.

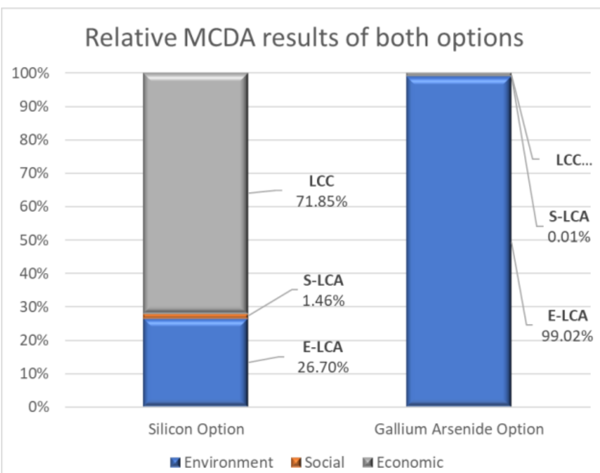

Figure 10: Relative LCIA results for the silicon and gallium arsenide options of the DOE/NASA SPS Reference System

The MCDA results indicate that costs were the most critical sustainability dimension for the silicon option, whilst the environment was the most critical for the gallium arsenide option. The total cost was roughly $3.86 trillion USD for each system. This includes considerable land acquisition costs for each rectenna site and worker salaries. Launch costs were around $407.00 USD per kg for the silicon option and $375.46 USD per kg for the gallium arsenide option at NPV due to vehicle reusability. However, since the solar cells of the gallium arsenide option costs considerably more than the silicon option, the cost of both systems become highly comparable. Despite this, the environment becomes by far the most impactful sustainability dimension for the gallium arsenide option. In this regard, the high environmental impact primarily stems from MRDP and HTP due to the use of germanium as a substrate in the solar cells for the reasons outlined in Section 5.1. These were responsible for 57.54% and 42.19% of the total environmental score, respectively. For comparison, ODP (51.54%) and WDP (45.05%) were the driving forces for the environmental score of the silicon option.

It could be argued that the vast change in importance levels between options either shows the severity of MRDP and HTP impacts in the gallium arsenide system or the influence and sensitivity of the normalisation factors and weighting approach used within the analysis. Additionally, social impacts were determined to be insignificant, but the top five most adversely impacted SDGs across both options were SDG 8 (Decent Work and Economic Growth), SDG 10 (Reduced Inequalities), SDG 12 (Responsibly Consumption and Production), SDG 16 (Peace, Justice and Strong Institutions) and SDG 17 (Partnerships For the Goals). This was mainly driven by the value chain actor stakeholder category due to evidence of anti-competitive behaviour, inconsistencies regarding payment to suppliers and sufficient lead times by companies in the United States at national-level. However, health & safety (the rate of fatal accidents, near misses and non-fatal accidents in the workplace) and the gender wage gap was also identified as problematic within the worker stakeholder category.

5.3 Annual Global Impacts vs Planetary Boundaries

Although MCDA was applied to determine which sustainability dimension is most impacted across each option of the DOE/NASA SPS Reference System, the application of AGIs and PBs can help to quantify the extent to which each impact category is affected. One major drawback of this approach is that the MRDP and HTP impact categories (along with several others listed in Section 3.3) are excluded from this analysis despite being identified as significant and a potential hotspot of the gallium arsenide option during MCDA. This is because they are yet to be defined by AGIs and/or PBs from a life cycle perspective.

Despite this, the total life cycle impacts of the remaining impact categories have been compared against AGIs and PBs for the silicon and gallium arsenide options using a heat map in Table 7 below. The values refer to the average annual life cycle impacts of the DOE/NASA SPS Reference System as a percentage of AGIs and PBs. In this case, the green shade indicates a value below 1.54% (the amount of global energy that the system is capable of providing relative to 2019 [15]) over each system's 30-year operational lifetime whilst the yellow shade denotes a value lower than 1.54% over the programme's 60-year operational lifespan. The orange shade represents values that are above 1.54% over 60 years but less than the AGI or PB, whilst the red shade is used for all values greater than the AGI or PB.

Table 7: Heat map comparing annualised life cycle impacts of the DOE/NASA SPS Reference System against AGIs & PBs

Impact Category	Si Option		Ga Option	
	AGI	PB	AGI	PB
AAP	6.71%	2.58%	13.85%	5.32%
GWP	0.50%	4.27%	0.55%	4.66%
ECIP	0.68%	0.11%	0.68%	0.11%
FEP	2.89%	2.52%	3.72%	3.25%
MEP	0.16%	0.16%	0.17%	0.17%
ODP	480.33%	143.74%	300.21%	89.84%
POP	3.42%	3.65%	3.54%	3.78%
OSP	0.04%	0.01%	0.02%	0.01%
FAETP	0.41%	2.53%	3.79%	23.59%
WDP	0.24%	1.82%	0.21%	1.63%

The results indicate that ODP is a particular hotspot of the DOE/NASA SPS Reference System. This is almost exclusively due to the release of ClO_x, NO_x and HO_x emissions from the burning of cryogenic propellant during launch event of the HLLV and PLV (particularly resulting from the LOX/CH_4 formulation). The rest of the impact categories have distinctly lower values, but most are not proportional to the market share of technology's global energy provision, even over the programme's 60-year operational lifespan. In particular, consideration may have to be given to the AAP, GWP, FEP, POP and FAETP impact categories in the design of future SPS systems. In a similar manner to the baseline findings, the production and decommissioning of the rectenna is responsible for a large proportion of these impacts. For the silicon option it contributes around 49.90% of the APP value, 65.95% of the GWP value, 61.44% of the FEP value, 58.99% of the POP value and 72.74% of the FAETP value. For the gallium arsenide option, it represents around 48.34% of the APP value, 60.38% of the GWP value, 47.71% of the FEP value, 57.00% of the POP value and 77.99% of the FAETP value. This suggests that addressing the impacts stemming from the rectenna may have to be addressed as a priority action.

Interestingly, WDP did not present itself as being particularly problematic despite being one of the driving forces for the environmental dimension of the silicon option, identified through MCDA. In this regard, WDP it can be seen to be more critical at a European level since water withdrawals there are higher than the global average. Additionally, it can be seen that the social and economic impacts did not present themselves as a hotspot. This does not mean that they are not critical. On the contrary, it may suggest that more comparable AGIs and PBs need to be defined for social and economic impacts.

5.4 Comparative Analysis

In order to benchmark the relative performance of the DOE/NASA SPS Reference System as part of the conventional energy mix, the CO_2e emissions and costs have been compared to terrestrial energy generation systems. In terms of CO_2e emissions, it was found that the silicon option produces 112.27 gCO_2e/kWh whilst the gallium arsenide option produces 122.63 gCO_2e/kWh. Based on OpenEI data [30,31], these values have been compared to the CO_2e produced by other terrestrial energy technologies in Figure 11 below. These values suggest that both SPS systems produce comparatively more CO_2e/kWh than renewables, but significantly less than fossil fuels. Additionally, the calculated value of the silicon option is over 5.62 times higher than the prediction of 20 gCO_2e/kWh for the DOE/NASA SPS Reference System made by Asakura et al. [17] whilst the calculated value for the gallium arsenide option is 6.13 times higher.

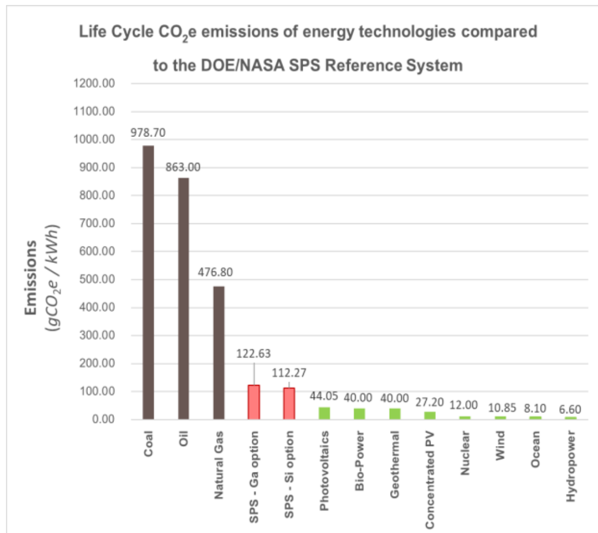

Figure 11: Life Cycle CO_2e emissions of energy technologies compared to the DOE/NASA SPS Reference System

In line with the goals of SBSP, these figures can then be used to identify the amount of CO_2e that an SPS could offset if the technology was used to directly replace a fossil fuel energy system with the same installed capacity. Under such a scenario, even when factoring in the amount of CO_2e emitted by the DOE/NASA SPS Reference System itself to the calculation, the silicon option could offset 28.21-67.06 gigatonnes of CO_2e ($GtCO_2e$) whilst the gallium arsenide option could offset 27.41-66.26 $GtCO_2e$ on average over its lifetime. This equates to an average annual reduction of 0.94-2.24 $GtCO_2e$ and 0.91-2.21 $GtCO_2e$ over each system's 30-year operational lifespan. For comparison, total global greenhouse gas (GHG) emissions in 2018 (including from land-use change) was 55.3 $GtCO_2e$ according to the United Nation Environment Programme (UNEP) 'Emissions Gap Report 2019' [53]. This means that the silicon and gallium arsenide systems are capable of offsetting around 1.70-4.05% and 1.65-4.00% of global annual GHG emissions respectively.

Additionally, Figure 12 illustrates that if the mission were to be extended 20 years, the carbon footprint of the technology would fall to 72.67 gCO_2e/kWh for the silicon option and 78.89 gCO_2e/kWh for the gallium arsenide option. It would take a mission extension of 67 years for the silicon option to overtake terrestrial-based PVs and 77 years for the gallium arsenide option. This equates to a mission lifetime of 97 years and 107 years respectively, a prospect which is currently hard to envision.

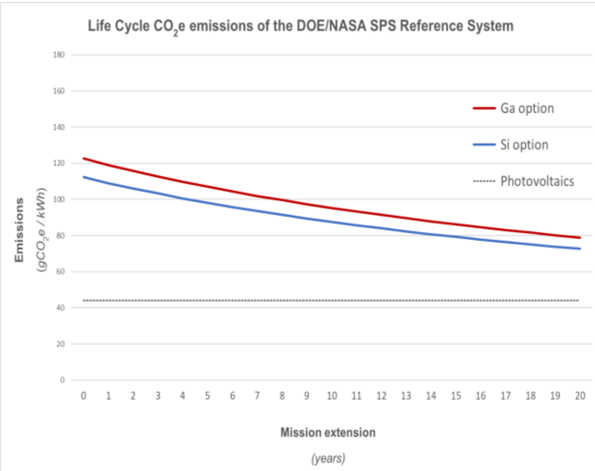

Figure 12: Life Cycle CO2e emissions of the DOE/NASA SPS Reference System

In terms of the cost comparison, the LCOE has been determined for the DOE/NASA SPS Reference System and compared to terrestrial energy systems, calculated in USD (CY:2015) and adjusted for inflation/exchange rates. LCOE is the minimum constant price at which electricity must be sold in order to break even over the lifetime of a project [54,55]. The application of the approach allows comparisons to be made between different energy generation systems on a consistent basis. In this case, it has been used to compare the costs of the DOE/NASA SPS Reference System to terrestrial energy generation systems in order to benchmark the relative performance of the technology as part of the conventional energy mix. It has been calculated at net present value by divided the sum of costs by the energy output of the DOE/NASA SPS Reference System over its lifetime, as exemplified in Eq. 4 below:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad \text{Eq. 4}$$

where C_t is the total costs of the system in year t, E_t is the energy generated in year t, r is the discount and exchange rate and n is the expected lifetime of the system. The result of this process shows that the LCOE for the silicon option is \$0.0457/kWh and \$0.0455/kWh for gallium arsenide option, as presented in Figure 13.

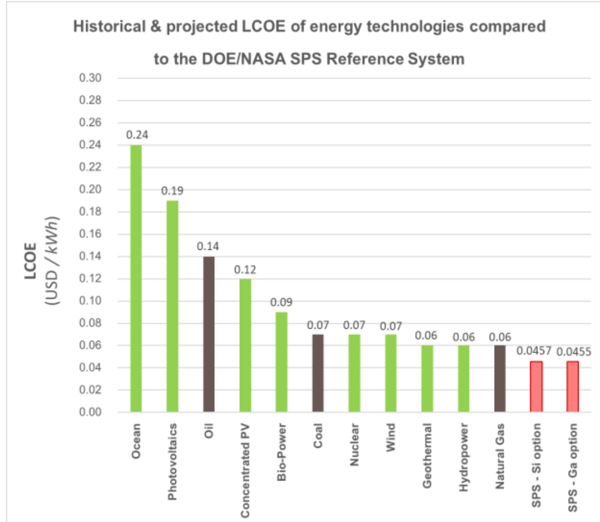

Figure 13: Historical/projected LCOE of energy technologies compared to the DOE/NASA SPS Reference System

It should be noted that the LCOE values reflect wholesale price only excluding the manufacturer's profit. This typically makes up around 35-45% of total costs, with the rest coming from a mixture of network costs, operational costs, governmental environment & social obligation costs, VAT and supplier profit. Based on this, it reasonable to assume that the energy generated from each SPS option could be sold continually for around \$0.1109-0.1432/kWh over the programme's lifetime (depending on the cost breakdown structure) with respect to the value of the USD at NPV. This is comparable to the current cost of electricity in the United States, which averages at around \$0.1319/kWh [56].

Despite this, one of the major drawbacks of the technology has traditionally been its high capital costs, even when considering economy of scale. As such, it may be advantageous to compare capital costs of the DOE/NASA SPS Reference System with other large, modern, state-of-the-art energy generation projects of a similar nature. In this sense, the two of the most comparable terrestrial projects are Ouarzazate Solar Power Station (the world's largest concentrated solar power plant) and Topaz Solar Farm in San Luis Obispo County, California (one of the largest solar farms in the world). Ouarzazate Solar Power Station has an installed capacity of 510 MW, with an additional 72 MW PV system to produce 582 MW at peak. It has a predicted capacity factor of up to 37% [57]. The total capital costs are estimated at around \$2.68 billion USD according to the World Bank [58]. Topaz Solar Farm has an installed capacity of 550 MW and generated about \$2.40 billion USD in capital costs. It has a capacity factor of around 26.6% [59,60].

Figure 14 below compares the capital costs of the DOE/NASA SPS Reference System with each of these energy generation projects. As can be seen, the silicon and gallium arsenide options have a much higher cost per kW. This is also is slightly higher in comparison to the cost estimate made as part of the CDEP at NPV [20]. However, this may be because more overheads were covered by this analysis.

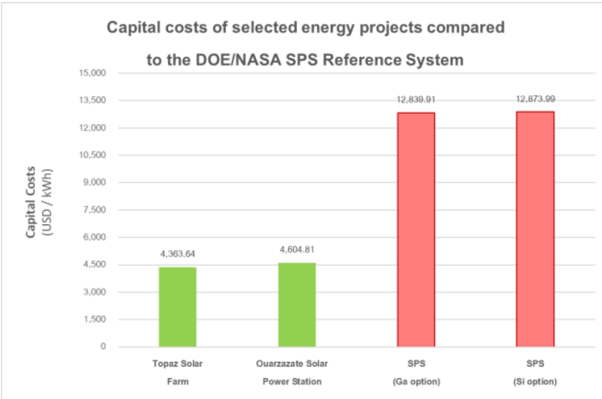

Figure 14: Capital costs of selected energy projects compared to the DOE/NASA SPS Reference System

This highlights that the capital costs per kW of the DOE/NASA SPS Reference System would be almost three times as much as the Topaz Solar Farm and Ouarzazate Solar Power Station for both options. This is in stark contrast with the significantly lower LCOE value obtained by each SPS option in comparison to such energy technologies. However, this disparity is easily explained by the higher capacity factor of the DOE/NASA SPS Reference System, which drives the low LCOE value and significantly reduces the payback period. Based on this, if each SPS were to be charged at the current cost of electricity in the United States, this provides a payback period of around 25.7 years for both options over the 60-year programme lifetime defined by Figure 1. A total surplus of $6,343.01 billion USD for the silicon option and $6,353.23 billion USD for the gallium arsenide option at NPV would therefore be generated. This means the overall system cost would represents around 37.85% of the total consumer cost for silicon option and about 37.75% for gallium arsenide option. Assuming the manufacturer's profit takes the wholesale value of each system to 40%, the total profit for the energy generation will be $219.43 billion USD and $229.63 billion USD, respectively, at NPV. The rest of the surplus would then be distributed according the elements of a predefined cost breakdown structure (as previously mentioned).

6. Evaluation & Reflection

6.1 Interpretation of Life Cycle CO_2e & Cost Impacts

Although the findings of this analysis suggest that the CO_2e emissions and LCOE of the DOE/NASA SPS Reference System is comparable with renewables, it is important to establish whether this technology fits into the current global political agenda on climate change. In terms of internationally agreed upon temperature goals, the Paris Agreement aims to limit global warming to well below 2°C above pre industrial levels by 2100, with efforts to limit this further to 1.5°C [61]. In order to achieve this, a limit must be set on the amount of CO_2e that the world can emit over this period. This is defined as the "carbon budget." According to a special report by the Intergovernmental Panel on Climate Change (IPCC) [62], to have a likely chance (67%) of limiting warming to 2.0°C, the world can emit 1,320 $GtCO_2e$ between 2018 and 2100 [63]. The remaining budget drops to 570 $GtCO_2e$ if warming is to be limited to 1.5°C.

In order to gauge whether the DOE/NASA SPS Reference System is capable of expediting efforts to achieve the Paris Agreement and its temperature goals, the amount of CO_2e produced by the silicon and gallium arsenide options can be examined next to these figures. For a fair comparison, since each system is active over 2040-2100, the carbon budgets need to be adjusted for this period. Assuming an even distribution of the carbon budgets from 2018 to 2100, then this means that under the 2.0°C pathway that 966 $GtCO_2e$ can be emitted whilst 417 $GtCO_2e$ can be emitted under the 1.5°C pathway. Table 8 provides an overview concerning the amount of CO_2e released by the silicon and gallium arsenide options in relation to the recalculated carbon budgets of both the 1.5°C and 2.0°C pathways.

Table 8: System contributions to IPCC carbon budgets

System	Emissions ($GtCO_2e$)	Percentage of 1.5°C pathway carbon budget	Percentage of 2.0°C pathway carbon budget
Si	8.69	2.08%	0.90%
Ga	9.49	2.28%	0.98%

Given that the system is capable of providing 1.54% of global energy consumption in 2019 [15], then assuming that the world population grows to 11.2 billion by 2100 in line with the predictions of the UN [64], the DOE/NASA SPS Reference system will be capable of producing 1.06% of global demand by 2100. As such, this figure can be used as a gauge for the percentage of the carbon budget allocated to each system. Based on this, the values contained within Table 8 indicate that the DOE/NASA SPS Reference System would not be able to actively contribute to the highly ambitious 1.5°C target without a significant rise in the abundance of carbon sinks. Despite this, either system is more than capable of contributing to the 2.0°C target since the size of market served is considerably greater than the share of the remaining carbon budget which would be allocated to the selected technology. In this respect, the technology can be classed as 'green' energy system in accordance with the Paris Agreement since it is consistent with the mitigation pathway defined for limiting temperature increases to 2.0°C. It should be noted that these findings do not take into account the additional benefits that the system may provide as an emission abatement technology should it be used to directly phase out fossil fuels (as noted in Section 5.4).

With regards to economic impacts, several authors have attempted to assess the costs of meeting Nationally Determined Contributions (NDCs) in comparison to the temperature targets outlined with the Paris Agreement. NDCs are documents pertaining to the contribution that each individual Member State will make under the Paris Agreement. When taken collectively, these outline the global action that will be taken. However, since many NDCs are not yet properly costed, only estimations are currently available. In this regard, a study conducted by the International Justice Initiative at the University of Tasmania estimated a total cost of $4.43 trillion USD for developing countries alone to implement their current NDCs [65]. As a whole, the OECD estimates that $6.90 trillion USD per year is required to 2030 to meet all of the development goals and climate objectives of the Paris Agreement [66]. This equates to 7.87% of global GDP annually relative to 2019, which was $87.70 trillion USD according to World Bank data [67]. Similarly, the UNEP 'Emissions Gap Report 2019' [53] states that climate policies consistent with the 1.5°C target will require global energy system supply-side investments of up to $3.8 trillion USD per year on average over the 2016–2050 timeframe. Despite these high costs, this is better than inaction as research by Burke et al. [68] suggests that failure to achieve these temperature goals could reduce global GDP by more than 25% by 2100 whilst Wei et al. [69] state that such failure could cost up to $616.12 trillion by 2100.

Although the cost of the DOE/NASA SPS Reference System cannot be directly compared to the costs of implementing the Paris Agreement at present, it can be benchmarked against these indicative cost estimates for addressing climate change. Table 9 below provides an overview of this.

Table 9: System contributions to the costs of addressing climate change

Source	USD (trillions)	Si option	Ga option
OECD	103.50	3.73%	3.72%
UNEP	129.20	2.99%	2.98%
Wei et al.	616.12	0.63%	0.63%

Clearly, it can be seen that the cost of implementing the technology requires a greater proportion of the estimated budgets allocated to addressing climate change than the size of market the technology serves. However, these costs are significantly less than market share of the budget under the predicted cost of failure scenario; a future pathway which is becoming increasingly more likely since the Paris Agreement is currently not on track to achieve it's intended targets [70]. As such, more climate finance may become available in the near-future, at which point the suitability of SPS with regard to these updated budgets could be revaluated. However, these findings do not take into account the payback period or profit generated over the lifetime of the system (as noted in Section 5.4), which may make the system a more viable and cost-effective approach.

6.2 Discussion of Hotspots

Several design hotspots were identified within the analysis across the silicon and gallium arsenide options. The most pressing of these was found to be ozone depletion which is almost exclusively due to the release of ClO_x, HO_x and NO_x radical emissions from the burning of cryogenic propellant during the launch events. The release of these radicals is particularly troublesome since in 2009, Ravishankara et al. found that NO_x radicals from human activity can cause twice as much ozone depletion than the next leading ozone-depleting gas [71]. These findings are confirmed by the World Meteorological Organization who state that NO_x emissions are growing relatively steadily at present and are likely to remain a major contributor to ozone depletion throughout the 21st century [72]. This places a higher emphasis on replacing traditional propellants with high performance green propellants. However, an environmental trade-off analysis should be conducted to determine the extent of improvements or whether any burden-shifting effects would take place with respect to other impact categories.

The MCDA approach also uncovered that costs were the most critical sustainability dimension for the silicon option. In this regard, the extensive capital costs of each system were driving factors of each system, despite the LCOE being reasonable. This means that the high investment costs may be off-putting and limit stakeholder buy-in, potentially threatening the feasibility of the concept. As such, future SPS designs must be conscious of costs and lower them were possible, with an emphasis on keeping launch costs at a level calculated by this analysis. Despite this finding, and the similarities of costs between options, the MCDA approach suggested that the environment became the more critical sustainability option for the gallium arsenide option due to the use of germanium as a substrate in the solar cells. This led to severe mineral resource depletion and human toxicity impacts which primarily stemmed from the arsenic, dioxins and mercury released as part of its manufacturing process. This is a common finding of space mission which use germanium as a substrate [10]. Therefore, limiting, replacing or eradicating the use of germanium as a substrate in the gallium arsenide solar cells is recommended as an improvement measure.

Overall, it was found that the construction and decommissioning of the rectenna produced the greatest burden across the majority of impact categories due to the industrialised practices required to transform such a large area. The most impacting industrial processes were the production of concrete and steel, the casting of aluminium and steel, and the electricity consumption. Addressing this area therefore has the potential to directly target the other potentially adverse impact categories identified through normalisation procedures in Section 5.3, allowing them to fall into acceptable limits. These findings differ from previous EEIO analyses given that CO_2e emissions from the rectenna supersedes PV and propellant production as the most impactful element under a process-based methodology [17,18,73]. In this regard, the rectenna construction and decommissioning, along with the space transportation vehicle fleet and construction of the SPS units, were responsible for over 99% of the CO_2e emissions of both the silicon and gallium arsenide options, and over 90% of the costs.

Finally, it should be noted that these hotspots refer specifically to the DOE/NASA SPS Reference System, and not the SBSP concept as a whole. This technology is comprised of a number of elements within an overall architecture that resembles an extremely large but otherwise typical spacecraft of the 1960s and 1970s. As such, it is recommended that the sustainability impacts of newer, more advanced and less bulky concepts such as SPS-ALPHA and CASSIOPeiA are also investigated. This means that LCSA should be included as a mandatory component of any and all SPS mission design sessions in the future.

7. Conclusion

The results and analysis from a process-based LCSA of the SBSP concept have been presented, modelled based on the DOE/NASA SPS Reference System. This study is not intended to act as a justification or indictment of the SBSP concept. Rather, it should be used as an indicative benchmark as to the general sustainability of the technology.

However, overall, the results suggest that although the Reference System can generally be described as a 'green' and 'cost-effective' technology, a distinct number of design improvements can and should be made to lessen its life cycle impacts. In this regard, several design hotspots were identified across the silicon and gallium arsenide options, according to their source. These should be used as mission drivers to frame modern SPS designs.

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