JOURNAL OF THE BRITISH INTERPLANETARY SOCIETY • VOLUME 76 2023 PAGES 18-28

Life Cycle Assessment of the UK Space Energy Initiative Technology Roadmap

ANDREW R. WILSON[1,2], MASSIMILIANO VASILE[2], HAROON B. OQAB[1] [1]Metasat UK Ltd, 21 Stravaig Path, Paisley, Renfrewshire, PA2 0RZ, United Kingdom; [2]Aerospace Centre of Excellence, Department of Mechanical & Aerospace Engineering, University of Strathclyde, 75 Montrose Street, Glasgow, G1 1XJ, United Kingdom

Email andrew@metasat.co.uk / andrew.r.wilson@strath.ac.uk

DOI https://doi.org/10.59332/jbis-076-01-0018

This paper aims to provide an overview of the environmental footprint of the UK Space Energy Initiative (SEI) technology roadmap based on the CASSIOPeiA solar power satellite (SPS) system using the life cycle assessment (LCA) methodology. The information covers the time period from 2022 to 2080 and is relevant for five stratospheric SPS prototypes, five low Earth orbit (LEO) SPS prototypes and twenty-five full-scale CASSIOPeiA systems which are capable of generating 2 gigawatts (GW) of power each and delivering this directly to the grid. Each CASSIOPeiA system has been modelled on the assumption that it will operate at 2.45 gigahertz (GHz) with 4-sun Concentrated Photo-Voltaic (CPV) variant in geostationary Earth orbit (GEO) for an average lifetime of thirty years. Primary data was collected from the SEI Technical Working Group and is considered to be representative of the current SEI technology roadmap. This information was collected using a simple Excel Spreadsheet titled 'SEI LCA 1.0'. The file contains relevant information pertinent to the content of this paper but was considered too large to attach as an annex. Despite this, it should be noted that whilst the majority of the collected data was considered to be robust and of a sufficiently high data quality, the manufacturing & production of the rectenna was mainly based on well-judged estimations and data extrapolations. The results indicate that the manufacturing & production of the offshore rectennas is a particular hotspot, drawing similarities to the findings of Wilson et al. (2020).

Keywords: Space Solar Power, Energy Systems, Life Cycle Assessment, Environmental Footprint, Ecodesign

1 INTRODUCTION

1 Background

To keep in line with the promises made under the Paris Agreement, the UK government passed legislation in June 2019 committing them to reach net-zero greenhouse gas (GHG) emissions by 2050 [1]. Achieving this target will require sustained policy interventions across multiple sectors, including energy supply, which currently accounts for around 21% of net GHG emissions in the UK [2,3]. In response to this challenge, the UK government recently commissioned new research into the technical and economic feasibility of space-based solar power (SBSP) as a potential contributor to net-zero [4]. Whilst that study highlighted that developing such a system is likely to be technically feasible, it is vitally important to determine the environmental credentials of the technology and whether it is capable of contributing to the UK's path to net-zero.

In this regard, the vast majority of previous life cycle assessment (LCA) studies on solar power satellite (SPS) concepts were based on an Economic Input-Output (EIO) analysis [5,6]. As discussed by Wilson (2022), EIO analyses are a highly inaccurate approach for measuring environmental impacts within the space sector, casting doubts on the validity of these results [7]. A more correct methodology is process-based analyses. Two process-based LCA databases currently exist – the European Space Agency (ESA) LCA Database and the Strathclyde Space Systems Database (SSSD) [8]. Additionally, only one process-based LCA analysis is known to have taken place on an SPS concept [9]. In this regard, the SSSD was used on the NASA/DOE SPS Reference System which is an extremely large, bulky and outdated spacecraft typical of 1960s/1970s architecture. Despite this, the concept was found to produce quite considerable environmental impacts, raising doubts on whether the technology could be described as 'green'.

For this reason, Metasat UK and the University of Strathclyde were commissioned by the UK Space Energy Initiative (SEI) to calculate the environmental footprint of modern SPS concepts based on the SEI technology roadmap using the process-based methods to determine whether SBSP can be an enabler for net-zero in the UK.

1.2 Aim & Purpose

The main aim of this paper is to synthesise the pertinent details of the LCA report which was produced as part of the SEI commissioned work [10]. The report quantified the overall en-

---

This paper was first presented at the 19th Reinventing Space Conference, 28-29 November 2022, Aerospace Bristol, Hayes Way, Patchway, Bristol, BS34 5BZ, UK.

vironmental impact of the SEI technology roadmap, using the CASSIOPeiA SPS concept [11] as a baseline. It is intended that the results will be integrated into the SEI technology roadmap to improve on the environmental performance and build space solar power systems in a manner that makes them as sustainable as technically possible. As defined by the SEI, there are two basic reasons for the outlined study approach. These are:

(1) To ensure that the SBSP concept can indeed help the UK to deliver net-zero.
(2) To justify potential future funding for the SEI technology roadmap.

Therefore, despite the potential vested interest of the SEI in this analysis, the practitioners of the study (Metasat UK and the University of Strathclyde) ensured that the study was conducted both professionally and vigorously with integrity maintained throughout to ensure that the analysis was grounded in scientific and factual principles to the furthest extent possible, based on the current state of knowledge.

In this regard, the study has been designed to comply with several guiding principles, including the ESA LCA guidelines as well as the ISO 14040:2006 and ISO 14044:2006 standards [12,13]. This will be described in more detail in the following sections of this paper.

2 GOAL & SCOPE

2.1 Goal Definition

The study was conducted to assess the life cycle environmental impacts of the SEI technology roadmap [14] (based on the CASSIOPeiA SPS system, including its rectenna) to determine whether the programme is a credible enabler for reaching net-zero in the UK. CASSIOPeiA stands for Constant Aperture, Solid – State, Integrated, Orbital Phased Array and is one of many existing SPS concepts [11]. The final selection of SPS concept has not yet been decided by the SEI. So, for the purposes of this assessment, the British CASSIOPeiA concept was used due to data availability. It should be noted that this system was used within this study as an example only to gain insights to the SBSP technology implementations.

The assessment will follow the LCA methodology which is a quantitative analysis relating to the environmental aspects of a product over its entire life cycle. Its purpose is to quantity the environmental impacts of the SEI technology roadmap for the period 2022-2080. Quantifying the environmental impacts of such a large programme at such an early stage of development may allow improvements to be made if there are any significant impacts, known as hotspots. By doing so, hotspots can be iteratively addressed, ensuring that the overall life cycle impact of the concept is reduced to the furthest extent possible.

LCA is internationally standardised through the ISO 14040:2006 and ISO 14044:2006 standards [12, 13]. However, the European Space Agency's 'Space system Life Cycle Assessment (LCA) guidelines' have adapted these standards to be more appropriate to the space sector without risking non-compliance [15]. As such, they should be seen as an extension of the ISO framework rather than an alternative to it. The guidelines are also orientated as closely as possible with the Product Environmental Footprint Category Rules (PEFCRs) developed by the European Commission [16, 17]. The PEFCRs were created in accordance with ISO 14040:2006 and 14044:2006 to provide specific guidance for calculating and reporting products' life cycle environmental impacts as part of the European Commission's work on harmonising LCA across European industries. Although no PEFCRs currently exist for space systems, general compliance with the methodological approach contained within this framework allows the ESA LCA guidelines to align more closely with the strategic goals of the European Commission.

The assessment has been carried out using a cradle-to-grave life cycle approach, taking all phases of the traditional space mission life cycle into account from Phase 0/A to Phase F. This includes complete coverage of the ground segment, launch segment and space segment as well as the rectenna infrastructure. This study should be seen as a stand-alone and descriptive assessment, which may eventually form part of an LCA series relating to the SEI technology roadmap.

The results were then used to calculate the CO_2e payback period and compare the programme's total carbon footprint to terrestrial energy generation systems to benchmark the technology's relative performance. Finally, the results were measured against UK targets to determine if the technology could act as enabler for net-zero GHG emissions.

Initially, the intended audience of the LCA report was the SEI core team and the CASSIOPeiA team. With the publication of this paper, this has now been extended to other interested stakeholders, including those in the space industry, renewable energy enterprises and the government. Therefore, according to the ISO 14040:2006 and ISO 14044:2006 standards [12,13], this means that the LCA must undergo a third-party critical review since comparative assertions are made with terrestrial energy systems. Although the underlying report has been reviewed internally by the SEI core team, this requirement has been included as a recommendation of the report, which is still to be fulfilled.

2.2 Scope of Study

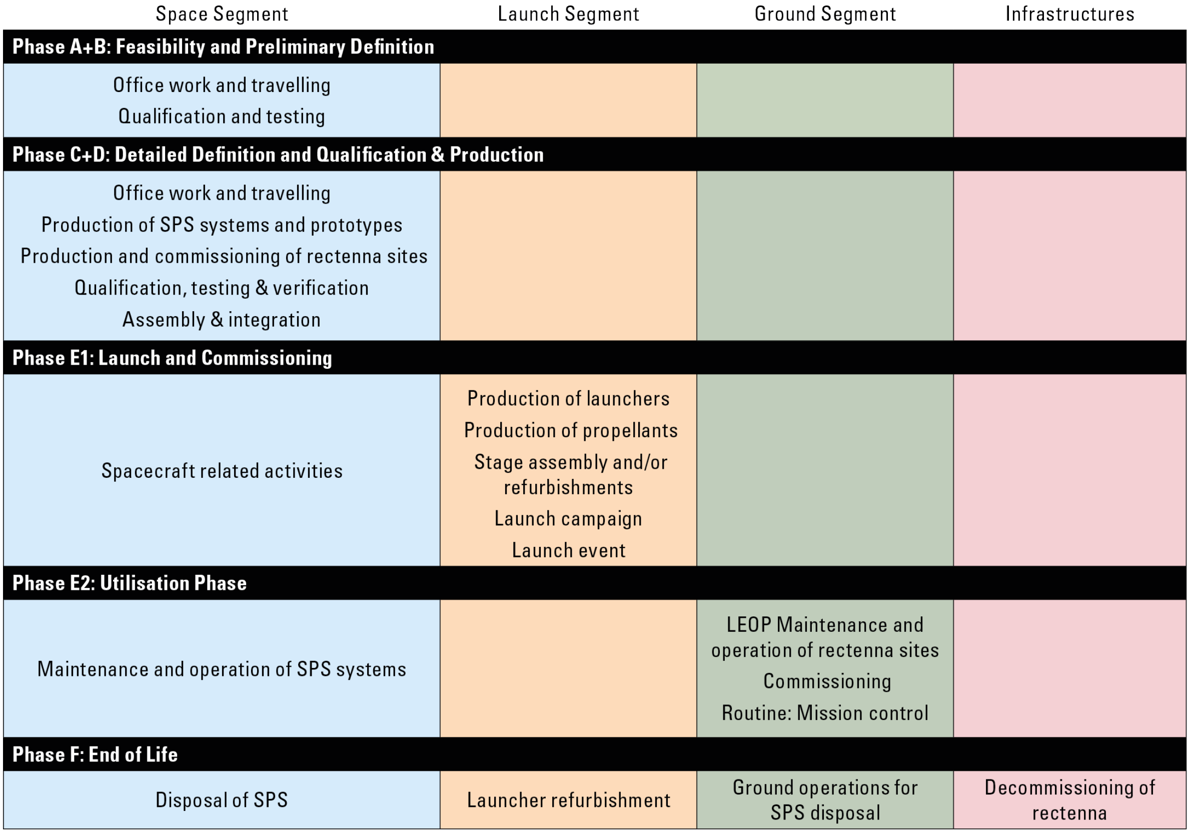
2.2.1 Functional Unit

The product system of this LCA is based on is the CASSIOPeiA SPS system and its associated prototypes. Together, their function is to provide wireless power from a space environment. As such, due to its orbit (GEO), the system is capable of providing near continuous power, only experiencing a small downtime during each equinox period and for general maintenance purposes.

To allow the results to be understandable and transparent, a common reference unit is required. This is referred to as the functional unit (FU) and is used as a quantified performance of a product system for use as a reference unit. As such, it defines what all inputs and outputs of the study should be related. Based on the ESA LCA guidelines [15], this has been defined for this study as follows:

"The SEI technology roadmap in fulfillment of its requirements."

In this sense, as previously mentioned, the SEI technology roadmap is relevant for the period 2022-2080 and refers to five stratospheric SPS prototypes, five LEO SPS prototypes and twenty-five full-scale CASSIOPeiA systems which are capable of generating 2 GW of power each and delivering this directly to the grid. Each CASSIOPeiA system has been modelled on the assumption that it will operate at 2.45 GHz with 4-sun Concentrated Photo-Voltaic (CPV) variant in GEO for an average lifetime of thirty years.



Space Segment	Launch Segment	Ground Segment	Infrastructures
Phase A+B: Feasibility and Preliminary Definition			
Office work and travelling Qualification and testing			
Phase C+D: Detailed Definition and Qualification & Production			
Office work and travelling Production of SPS systems and prototypes Production and commissioning of rectenna sites Qualification, testing & verification Assembly & integration			
Phase E1: Launch and Commissioning			
Spacecraft related activities	Production of launchers Production of propellants Stage assembly and/or refurbishments Launch campaign Launch event		
Phase E2: Utilisation Phase			
Maintenance and operation of SPS systems		LEOP Maintenance and operation of rectenna sites Commissioning Routine: Mission control	
Phase F: End of Life			
Disposal of SPS	Launcher refurbishment	Ground operations for SPS disposal	Decommissioning of rectenna

Fig.1 System Boundary of the UK SEI Technology Roadmap.

2.2.2 Functional Unit

The product system detailed within this paper includes the space segment, launcher segment and ground segment of all phases of a typical space mission architecture from Phase 0/A to Phase F. Infrastructure is also included due to the need for rectennas. All relevant processes are provided in Fig. 1, which is based on the ESA LCA guidelines [15].

The figure shows the initial flowchart of the study's system boundaries in relation to the different segments and phases. Specific activities which are included under each element can be found in Section 3.2, for which specific input data has been defined. Regardless, it is important to note that some life cycle stages which have been outlined in the system boundary will not be included as impacts within the model. For example, during end of life for the space segment, it is hypothesised that nothing will return to Earth, and therefore there is no impact from an ecospheric perspective.

2.2.3 Data Collection Procedures

It is important to note that data quality requirements differ per analysed activity. This depends on whether foreground or background data has been used. Foreground processes are processes that are specific for the product life cycle and for which direct information access is available. Background processes are processes that are not specific for the product life cycle and for which information is not directly accessible.

Within this study, foreground processes relate to the data contained within the Excel Spreadsheet titled 'SEI LCA 1.0' which is based on the data generated, calculated and produced as part of the SEI Technical Working Group. As such, this information is mainly considered to consist of primary data, with some proxies or estimations used. In comparison, background data was obtained from the Strathclyde Space Systems Database (SSSD) [18], which is a space-specific life cycle database developed at the University of Strathclyde. This mainly consists of secondary data and was also used for calculating the life cycle impacts of this study.

The SSSD is 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 [19], the SSSD has already been used in the design of several space missions. It consists of over 250 unique foreground space-specific life cycle sustainability datasets which each contain environmental, costing and social data (based on Ecoinvent and ELCD background inventories). 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 aligns closely with a variety of widely accepted international standards and norms, which are used as a coordinated, overarching framework [18].

The purpose of the tool is to identify sustainability hotspots quantitatively and scientifically as part of the space mission design process, and use this information to lower adverse environmental, social and economic life cycle 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 [18].

2.2.4 Assumptions and Limitations

To fulfil the system boundary several assumptions had to be made. This was due to data gaps and other elements which were considered outside the scope of the SEI technical working group's remit. These required a list of proxies to be used, each of which are indicated via a '[P]' within Section 3.2. The proxies were taken from well-judged estimates, expert knowledge or default values contained within the SSSD.

In addition to the data gaps there were a variety of limitations. The main one was the fact that the SSSD did not always contain a full list of Life Cycle Inventory (LCI) datasets required for specific components due to their uniqueness. Additionally, another drawback is the fact that the LCI datasets contained within the SSSD are mainly based on secondary sources. This was mostly driven by a lack of available or reliable data and/or willingness of companies to contribute data due to fear of being seen as the 'black sheep' of the industry. Moreover, due to the novelty and lack of scientific research on some topics, some flows were absent from SSSD LCI datasets meaning that placeholder flow indicators or proxies had to be used instead. An example of this is the rectenna since the SEI technical working group had not yet finalized a design. More specifically, the only data available related to the outdated NASA/DOE SPS Reference System. Instead, a conservative proxy design was used to reflect expected practice to furthest extent possible. Additionally, it should be noted that the environmental impacts of black carbon, aluminium oxide and water vapour from rocket propulsion have not been captured by the model due to the large uncertainties attached to their potential impact at different altitudes. This is particularly problematic as recent research has suggested that such impacts could be potentially meaningful. In terms of this model, water vapour emissions from launch could be a significant omission. However, this exclusion is a common problem in space LCA models, and not exclusive to the SSSD. Therefore, it is recommended that future studies of the SEI technology roadmap include such impacts if this information were to become available.

Moreover, on closer inspection of 'SEI LCA 1.0' data sheet, it is possible that the number of launchers and launch events may have been under-estimated. This is based on a small discretion which was noticed relating to the total mass of each CASSIOPeiA system and the total payload capacity of a standard SpaceX Starship to GEO. However, the numbers provided by the 'SEI LCA 1.0' data sheet have been used in this analysis regardless. It is proposed that this issue is investigated further in subsequent analyses and updated in future versions of the report on which this paper is based, if it is determined as being necessary.

Finally, it should be noted that all values contained within this assessment reflect the environmental impacts associated with current operating conditions. We make no attempt to predict potential future pathways, with particular reference to expected lowering carbon intensities in line with UK policy pledges. Instead, the investigation of future pathways may be considered as part of future versions of the underlying report, as well as other factors such as the impact of using alternative launch vehicles and integrating the potential role of black carbon to atmospheric processes.

2.2.5 Impact Categories and Assessment Methods

The life cycle impact assessment (LCIA) phase is used to translate the data contained in the LCI into environmental burdens. For this reason, the selection of impact categories and their associated methods dictate the orientation of the study. The categories generally relating to land, water, air, resources, and humans are given importance depending on the motive and context of the study.

Within this study, the impact categories and assessment methods were based on the recommendations contained within the ESA LCA guidelines and Wilson et al., (2021) [8,15]. An overview of these can be seen in Table 1 below. As can be seen, whilst the main focus of this assessment will be on Global Warming Potential (GWP), a wide variety of environmental media has been considered. These are considered to capture the main impacts of space systems across the space segment, launch segment, ground segment and infrastructures.

TABLE 1 Selected Impact Categories and Assessment Methods

Impact Categories	Unit	LCIA Method
Air Acidification	kg SO_2 eq	CML (2001) [20]
Aluminium Oxide Emissions	kg Al_2O_3	ESA (2016) [15]
Critical Raw Material Depletion	kg	SSSD (2019) [18]
Freshwater Aquatic Ecotoxicity Potential	PAF.m^3.day	USEtox [21]
Freshwater Eutrophication Potential	kg P eq	ReCiPe [22]
Global Warming Potential (GWP100)	kg CO_2 eq.	IPCC (2013) [23]
Human Toxicity Potential	cases	USEtox [21]
Ionising Radiation Potential	kg U^{235} eq	ReCiPe [22]
Marine Ecotoxicity Potential	kg 1,4-DB eq	CML (2001) [20]
Marine Eutrophication Potential	kg N eq	ReCiPe [22]
Ozone Depletion Potential (Steady State)	kg CFC-11 eq.	CML (2001) [20]
Particulate Matter Formation Potential	kg PM_{10}	ReCiPe [22]
Photochemical Oxidation Potential	kg NMVOC	ReCiPe [22]
Resource Depletion Potential (Fossil)	MJ fossil	CML (2001) [20]
Resource Depletion Potential (Mineral and Metal)	kg Sb eq	CML (2001) [20]
Water Depletion Potential	m^3	ReCiPe [22]

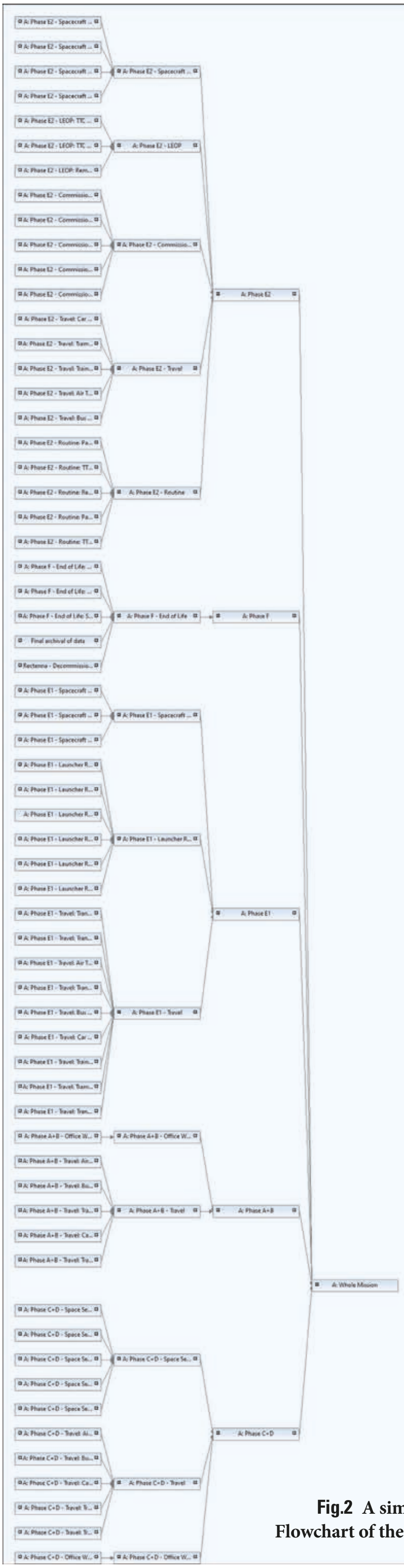


Fig.2 A simplified Process Flowchart of the System Model.

3 LIFE CYCLE INVENTORY ANALYSIS

3.1 Process Flowchart

A simplified Process Flowchart of the System Model is shown in Fig. 2.

3.2 Data Collection & Calculation Procedures

As mentioned in Section 2.2.3, the LCI was established using data contained within the Excel Spreadsheet titled 'SEI LCA 1.0'. This consisted of design information which was generated, calculated and produced as part of the SEI technical Working Group. The information contained within the Excel Spreadsheet was able to fulfil the entire system boundary mainly using primary data, with the use of some proxies and estimations. These proxies and estimations were conservative by nature and mainly used for elements not influenced by systems engineering such as man-hours and travel. A full list of the foreground data is outlined in Table 2, with all proxies and/or estimations indicated by a '[P]'.

Overall, the declared material list (DML) covered 100% of the SPS, launcher and rectenna product systems. All of the information mentioned above was input to the SSSD in OpenLCA, which was applied to provide space-relevant background data for the analysis and for the impact assessment calculation. The SSSD is based on an attributional, 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. This is applied using the 'At Point of Substitution' (APOS) allocation procedure. This procedure uses system expansion of product systems to avoid allocating within treatment systems. To do this, by-products substitute reference products as inputs to activities without further treatment. As such, all activities that have a material for treatment as an input will be handled in the same way. This is generally considered to be the most methodologically correct way to perform LCA. However, ESA currently apply cut-off since this is a more simplistic approach, thereby reducing the learning curve for engineers.

3.3. Data Quality Analysis

The assessment of the data quality is a vitally important aspect of the LCA methodology to ensure robustness of the data contained in the LCI. Data quality is typically synthesised within an LCA report as a summary table indicating percentage of data using specific data, generic data and proxies. To help the space industry with this process, ESA have produced a data quality matrix for space missions based on the pedigree approach, as informed by the Product Environmental Footprint Guide [16,17] and adapted by Petterson (2019), Chanoine et al. (2022) and TN CSCE-TN-ESA-ST-0024 [24, 25, 26].

As such, this approach has been applied as part of this study at system level to evaluate the robustness of data used within the LCI of the SEI technology roadmap. The LCI data has been qualitatively evaluated against the six data quality indicators contained within the ESA data quality matrix, which are:

- Technological Representativeness (TeR): the degree to which the dataset reflects the actual technology.
- Geographical Representativeness (GR): the degree to which the dataset represents conditions where the

TABLE 2: Lifecycle Inventory Foreground Data

Phase A+B		
Office Work	Man-hours	(1,400,000) [P]
Travel	Trips by air	(190) [P]
	Trips by bus	(24,931) [P]
	Trips by car	(217,233) [P]
	Trips by train	(1,115) [P]
Phase C+D		
Office Work	Man-hours	(700,000) [P]
Travel	Trips by air	(80)[P]
	Trips by bus	(17,840) [P]
	Trips by car	(83,848) [P]
	Trips by train	(892) [P]
Space Segment	Combined mass of all SPS/rectenna prototypes in tonnes	(2,265.25)
	Production of propellants/pressurants in tonnes	(736.12)
	Containment of propellants/pressurants in litres	(9,258,917.36)
	Decontamination/waste treatment of propellants/pressurants in tonnes	(736.12)
	General handling of propellants/pressurants in hours	(6,912)
	Storage of propellants/pressurants in m^3	(927.5112)
	Production and AIT of all SPS and rectennas in tonnes	(51,142.5) [P – rectennas]
Phase E1		
Launcher activities	Launcher selection	(SpaceX Starship)
	Number of launchers	(60)
	Total amount of LOX/LCH_4 propellant in tonnes	(682,800)
	Total number of launch events	(569)
Spacecraft activities	Man-hours during launch campaigns	(60,612,720) [P]
	Loading spacecraft onto launcher in number of items	(569)
	Total mass of spacecraft container in kg/reuse	(11,308.75) [P]
Travel	Trips by air	(840) [P]
	Trips by bus	(936,600) [P]
	Trips by car	(777,378) [P]
	Trips by train	(18,732) [P]
	Consumables to launch site via lorry in t*km	(28,367,953,674.5) [P]
	Consumables to launch site via transoceanic ship in t*km	(19,243,933,887.8) [P]
Phase E2		
LEOP	TTC control centre man-hours	(63,360) [P]
	TTC ground station use	(29,905) [P]
Commissioning	Payload data control centre man-hour	(5,700) [P]
	Payload data handling station use	(5,138) [P]
	Remote terminal in man-hours	(4,800) [P]
	TTC control centre man-hours	(6,360) [P]
	TTC ground station use	(5,732) [P]
Routine	Payload data control centre man-hour	(7,862,400) [P]
	Maintenance of spacecraft and rectenna in percentage of time	(2) [P]
Travel	Trips by air	(1,200) [P]
	Trips by bus	(267,600) [P]
	Trips by car	(1,110,540) [P]
	Trips by train	(26,760) [P]
Phase F		
End of Life Operations	Total number of launcher first stages recovered	(569)
	SPS and rectenna decommissioning in number of items	(26.0825)
	Ground operations in man-hours	(31,299) [P]
	Final archival of data in years	(30) [P]

process is indicated to be conducted.

- Temporal Representativeness (TiR): the degree to which the data represents certain years or period and whether variation is expected between time periods.
- Completeness (C): the degree to which the dataset covers all relevant impacts.
- Precision/uncertainty (P): the degree to which there is variability between data values.
- Methodological appropriateness and consistency (M): the methodological approach matches the intended use and purpose of the data.

Each of these data quality indicators can be ranked numerically according to a list of predefined criteria. These quality levels are based on a tiered-approach, where:

- Very Good: data meets the criterion to a very high degree, without need for improvement.
- Good: data meets the criterion to a high degree, with little significant need for improvement.
- Fair: data meets the criterion to an acceptable degree, but merits improvement.
- Poor: data does not meet the criterion to a sufficient degree and requires improvement.
- Very Poor: data does not at all meet the criterion, with the need for substantial improvement.

The list of predefined criteria for each data quality indicator can found in Table 3, alongside the score associated with the achieved quality level (quality rating) for the SEI technology roadmap. All of the data quality indicators were evaluated through qualitative expert judgment. Based on this, a compacted data quality ranking (DQR) can be calculated for each dataset to provide an overall data quality level. This is based on

TABLE 3: Compacted Data Quality Ranking (DQR)

Overall data quality rating (DQR)	Overall data quality level
≤1.6	High quality
>1.6 to ≤3.0	Basic quality
>3.0 to ≤4.0	Data estimate

TABLE 4: Data Quality Matrix covering the Life Cycle Inventory (LCI) of the UK SEI Technology Roadmap

Quality	Quality Rating	(TeR)	(GR)	(TiR)	(C)	(P)	(M)
Very Good	**1**	Technology aspects have been modelled using data from enterprises, processes and materials under study.	Involves data from the specific area under study.	All the data sources refer to the defined time and are ≤3 years of difference to the year of study.	>80% of process completeness determined flows have been evaluated and given a value.	Very low uncertainty and/or very high precision (≤10%).	Inclusion of all LCA stages (with the EoL stage). Consideration of allocation procedures. Completion to a very high degree.
Good	**2**	Technology aspects have been modelled using data from processes and materials under study, but from different enterprises.	Involves average data from a larger area in which the area under study is included.	Most of the data sources refer to the defined time and are 3 to 6 years difference.	60-79% of determined flows have been evaluated and given a value.	Low uncertainty and/or high precision (10%-20%).	Inclusion of most LCA stages. Consideration of allocation procedures. Completion to a high degree.
Fair	**3**	Technology aspects have been modelled using data from processes and materials under study, but from different technology.	Involves data from an area with similar production conditions.	At least half of the data sources refer to the defined time and are 5 to 10 years difference.	40-59% of determined flows have been evaluated and given a value.	Fair uncertainty and/or fair precision (20-30%).	Inclusion of a sufficient amount of LCA stages. Consideration of allocation procedures. Completion to a sufficient degree.
Poor	**4**	Technology aspects have been modelled using data related to processes or materials, using the same technology.	Involves data from an area with slightly similar production conditions.	Less than half of the data sources refer to the defined time and are 10 to 15 years difference.	<40% of determined flows have been evaluated and given a value.	High uncertainty and/or low precision (30-50%).	Inclusion of a low amount of LCA stages. Consideration of allocation procedures. Completion to a low degree.
Very Poor	**5**	Technology aspects have been modelled on related processes or materials but different technology or unknown.	Involves data from unknown area or area with very different production conditions or unknown.	None of the data sources refer to the defined time or age of the data is unknown.	Process completeness not scored or unknown.	Very high uncertainty and/or very low precision (>50%) or unknown.	Inclusion of LCA stages insufficient. No consideration of allocation procedures (multi-functionality has not been solved according to the situational context).

TABLE 5: Life Cycle Impact Assessment Results

Impact Categories	Unit	LCIA Method	Mission Phase					
			A+B	C+D	E1	E2	F	Total
Air Acidification	kg SO_2 eq	CML (2001)	1.91E+04	1.27E+09	1.40E+08	8.38E+04	6.56E+07	1.48E+09
Aluminium Oxide Emissions	kg Al_2O_3	ESA (2016)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Critical Raw Material Depletion	kg	SSSD (2019)	3.69E+03	2.04E+08	1.23E+07	1.94E+04	2.32E+06	2.19E+08
Freshwater Aquatic Ecotoxicity Potential	PAF.m^3.day	USEtox	5.39E+07	1.53E+13	8.30E+10	3.41E+08	2.85E+10	1.54E+13
Freshwater Eutrophication Potential	kg P eq	ReCiPe	2.44E+03	2.21E+08	9.58E+06	2.30E+04	4.23E+06	2.34E+08
Global Warming Potential (GWP100)	kg CO_2 eq.	IPCC (2013)	5.57E+06	2.77E+11	3.51E+10	3.37E+07	9.61E+09	3.22E+11
Human Toxicity Potential	cases	USEtox	2.10E+00	2.66E+09	6.69E+03	1.41E+01	2.00E+03	2.66E+09
Ionising Radiation Potential	kg U235 eq	ReCiPe	1.88E+06	5.40E+10	6.50E+09	5.08E+06	2.48E+09	6.30E+10
Marine Ecotoxicity Potential	kg 1,4-DB eq	CML (2001)	6.08E+09	2.78E+16	2.45E+13	4.15E+10	1.45E+13	2.78E+16
Marine Eutrophication Potential	kg N eq	ReCiPe	4.76E+03	2.55E+08	3.43E+07	2.74E+04	1.06E+07	3.00E+08
Ozone Depletion Potential (Steady State)	kg CFC-11 eq.	CML (2001)	6.07E-01	1.67E+04	1.73E+08	3.77E+00	4.01E+02	1.73E+08
Particulate Matter Formation Potential	kg PM10	ReCiPe	6.97E+03	7.27E+08	4.88E+07	3.27E+04	1.68E+07	7.92E+08
Photochemical Oxidation Potential	kg NMVOC	ReCiPe	1.43E+04	8.81E+08	1.06E+08	7.36E+04	3.23E+07	1.02E+09
Resource Depletion Potential (Fossil)	MJ fossil	CML (2001)	7.05E+07	2.98E+12	4.59E+11	4.13E+08	1.09E+11	3.55E+12
Resource Depletion Potential (Mineral and Metal)	kg Sb eq	CML (2001)	1.76E+03	3.61E+11	1.85E+06	9.73E+03	8.41E+04	3.61E+11
Water Depletion Potential	m^3	ReCiPe	2.08E+07	2.22E+12	9.61E+10	7.71E+07	3.31E+10	2.35E+12

the scoring of each data quality indicator. The formula below provides the calculation provision:

$$DQR = \frac{TeR + GR + TiR + C + P + M + Xw * 4}{i + 6} \tag{1}$$

where *TeR, GR, TiR, C, P, M* refer to the data quality indicators, *Xw* is the weakest data quality level obtained, and I is the number of applicable data quality indicators.

The DQR result can be used to identify the corresponding quality level in Table 4. According to ESA, a minimum quality of “Fair” (rating of 3.0) in each data quality indicator, as well as an overall basic quality is considered the minimum requirement to maintain data quality.

Based on this information, the LCI of this study generates a DQR of 1.83 which, according to Table 3, is defined as basic quality. This result reaffirms that an applicable level of robustness of the LCI data was achieved, allowing for informed conclusion to be drawn.

However, the method outlined to assess data quality and uncertainty in space LCA is still somewhat primitive. In this regard, an ESA co-funded project is about to kick-off at the University of Strathclyde which will define more robust methods for quantifying data quality and uncertainty as part of the space LCA concept.

4 LIFE CYCLE IMPACT ASSESSMENT

Table 5 shows the LCIA results generated for the SEI Technology Roadmap across a wide variety of environmental impact categories and life cycle phases.

5 INTERPRETATION

5.1 Hotspot Analysis

To gauge the severity of the impacts stated in Table 3, normalisation was applied. Normalisation relates the LCIA results of each impact category to a certain reference value in order to make results more understandable. In this case, the LCIA results of the entire SEI technology roadmap were compared against planetary boundaries. Planetary boundaries are used to highlight anthropogenic perturbations of the Earth system in relation to safe operating thresholds/tipping points [27].

When comparing the LCIA results, it was found that all but two impact categories were within 5% of the planetary boundary value provided by the European Commission [28]. These were ozone depletion potential (32.16%) and freshwater aquatic ecotoxicity potential (11.76%), highlighting these impact categories as potential hotspots. In particular, the ozone depletion impact stemmed almost entirely from exhaust emissions produced during the launch events which was responsible for 99.99% of the result. This came from ClO_x, HO_x and NO_x radical compound releases from the combustion of cryogenic propellant. For freshwater aquatic ecotoxicity potential, the impact came mainly from the use of germanium as a substrate in the solar arrays during Phase C+D (66.52%). This was directly attributable to the release of arsenic, mercury, lead, zinc and dioxins to air from germanium production & manufacturing. Despite this, due to the nature of the technology used, it is natural that the global warming potential results will generate the most interest. In this regard, global warming potential represented just 4.74% of the planetary boundary for climate change. Phase C+D was responsible for 86.10% of the total impact of

global warming potential, with the production and manufacturing of the rectenna representing 77.73% of the total. This was due to the turning of aluminium (11.22%), turning of steel (39.81%) and casting of aluminium (16.66%) processes mainly due to the release of fossil carbon dioxide, fossil carbon monoxide, fossil methane, HFC-116 and R-14 emissions to air.
As such, going forward, it is critical that the ozone depletion and freshwater aquatic ecotoxicity impact categories are treated with the same level of severity as global warming potential. The most contributing factors of each impact category outlined in Table 3 are contained within the SEI commissioned report.

5.2 Comparative Analysis

As one of the purposes of this analysis is to ensure that the SBSP concept can help the UK to deliver net-zero, this places an added emphasis on the global warming potential (GWP) results. In this regard, recent projections have shown that the cumulative actions taken under the Paris Agreement will fall well short of the 1.5°C and 2°C degree targets, leading to 2.7°C of heating by the end of the century – a potentially catastrophic scenario [29]. Moreover, the Climate Change Committee recently confirmed that the UK is not on track to meet its carbon budget targets in 2025 and 2030 [30]. In this respect it was found that the SEI programme would produce a total carbon footprint of 322,013,622,430.981 kg CO_2 eq., which equates to 79.4% of the UK's entire carbon footprint in 2020 [3]. If this were to be annualised over the lifetime of the SEI programme, the average yearly carbon footprint equates to ~1.4% of the UK's carbon footprint in 2020.

Despite this, the UK currently has an installed capacity of 75.8 GW of electricity [31], with the SEI potentially able to provide an additional 50 GW. Therefore, this is a modest amount of CO_2e given the vast amount of additional installed capacity the programme could provide. Additionally, the project may even allow emissions to be reduced if used to directly phase out fossil fuels. Since a total of 1.37E+13 kWh of energy would be produced by the programme as a whole, this means that the total carbon footprint of the SEI programme is 23.56614576 gCO_2e/kWh. This compares to an average carbon intensity of 233 gCO_2e/kWh for the UK energy fuel mix [32]. When evenly distributing the total CO_2e emitted by the SEI technology roadmap over its 58-year lifespan as a constant, it can be hypothesised that the carbon payback period will be less than 6 years based on the average UK figure.

Converting the carbon footprint into such units allows the value to be compared to other energy technologies. In this regard, a recent report by the United Nations Economic Commission for Europe (UNECE) examined the life cycle CO_2e produced by all energy technologies [33]. The technologies assessed include coal, natural gas, hydropower, nuclear power, concentrated solar power (CSP), photovoltaics, and wind power. Twelve global regions were included in the assessment, allowing for the variation of load factors, methane leakage rates, or background grid electricity consumption, among other factors. The results of this study are outlined in Figure 3.

Some highlights of this study are outlined below:

Fossil fuels

- Coal power shows the highest scores, with a minimum of 751 gCO_2e/kWh (IGCC, USA) and a maximum of 1,095 gCO_2e/kWh (pulverised coal, China). Equipped with a carbon dioxide capture facility, and accounting for the CO_2 storage, this score can fall to 147-469 gCO_2e/kWh (respectively).
- A natural gas combined cycle plant can emit 403–513 gCO_2e/kWh from a life cycle perspective, and anywhere between 49 and 220 gCO_2e/kWh with CCS. Both coal and natural gas models include methane leakage at the extraction and transportation (for gas) phases; nonetheless, direct combustion dominates the lifecycle GHG emissions.

Nuclear power

- Nuclear power generates less CO_2 emissions over its life cycle than any other electricity source. It also shows less

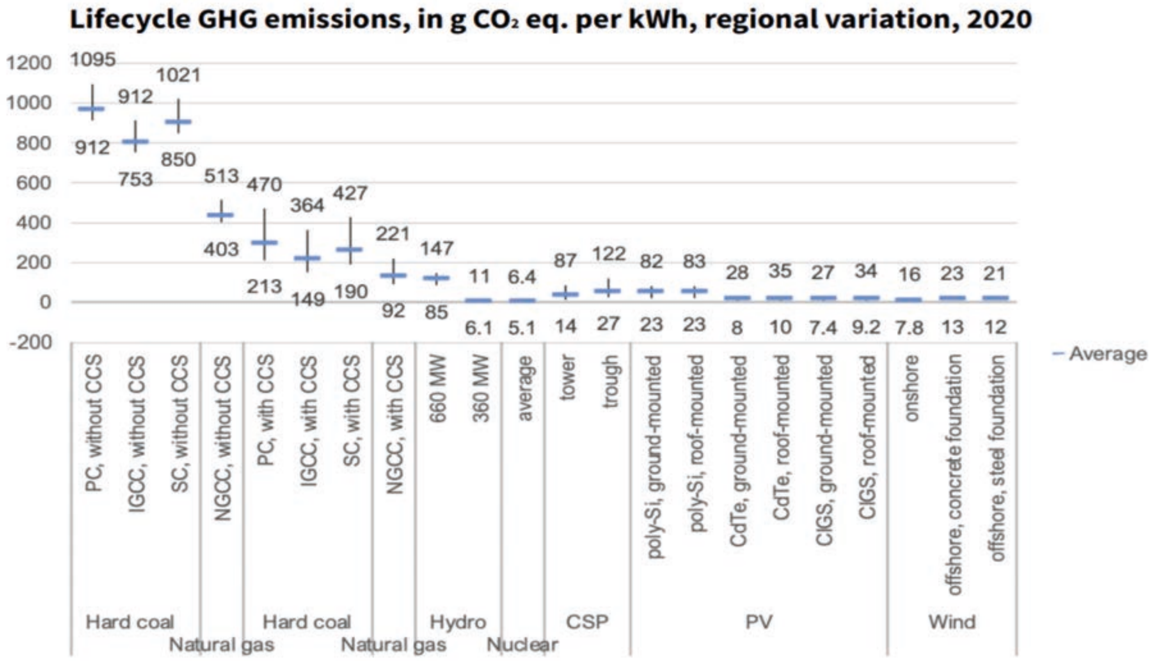


Fig.4 Life Cycle GHG emissions of energy technologies [31].

variability because of the limited regionalisation of the model, with 5.1–6.4 gCO_2e/kWh, the fuel chain ('front-end') contributes most to the overall emissions.

Renewable technologies

- Most renewable technologies GHG emissions are embodied in infrastructure (up to 99% for photovoltaics), which suggests high variations in lifecycle impacts due to raw material origin, energy mix used for production, transportation modes at various stages of manufacturing and installation, etc.
- Hydropower shows the most variability, as emissions are highly site-specific, ranging from 6 to 147 gCO_2e/kWh. As biogenic emissions from sediments accumulating in reservoirs are mostly excluded, it should be noted that they can be very high in tropical areas.
- Solar technologies generate GHG emissions ranging from 27 to 122 gCO_2e/kWh for concentrated solar power (CSP), and 8-83 gCO2e/kWh for photovoltaics, for which thin-film technologies are sensibly lower-carbon than silicon-based PV. The higher range of GHG values for CSP is probably never reached in reality as it requires high solar irradiation to be economically viable (a condition that is not satisfied in Japan or Northern Europe, for instance).
- Wind power GHG emissions vary between 7.8 and 16 gCO_2e/kWh for onshore, and 12 and 23 gCO_2e/kWh for offshore turbines.

As can be seen from Figure 3 and the highlights of the study outlined above, the estimated 23.6 gCO_2e/kWh places the SEI programme on a comparable footing with renewable energy technologies. However, the system boundary of this study had a wider scope than the UNECE study, also including aspects such as design activities. Despite these, these additional activities have a completely insignificant effect on the results (<1%). Overall, this would suggest that the SEI technology roadmap is capable of contributing to net-zero in the UK, at least from an environmental perspective, since it offers large amounts of low-emission baseload power. However, it is important to note that this technology should not be seen as a 'holy-grail' solution or be compared to renewables for any kind of justification on the basis of an 'us versus them' scenario. Instead, SBSP must be part of a mix of energy sources, thereby ensuring increased stability and security of the national grid.

6 CONCLUSIONS, RECOMMENDATIONS & NEXT STEPS

Over the lifetime of the programme, the total carbon footprint has been calculated to be 23.6 gCO_2e/kWh, which was found to be similar to other renewable energy technologies. This also can be compared to the 112.3 gCO_2e/kWh carbon footprint of the silicon option of the NASA/DOE Reference System and 122.6 gCO_2e/kWh for the gallium arsenide option based on the same methodology and calculation tool [9]. The main reason for this difference is the modernisation of the design. This refers mainly to the reduced volumes of steel, aluminium and concrete required for the rectenna, and the hyper-modular and autonomous assembly of the CASSIOPeiA concept, eliminating the need for humans to be stationed in space.

Overall, the results suggest that whilst the SEI technology roadmap could potentially contribute to the delivery of UK net-zero emissions, and by extension global efforts to combat climate change, several design improvements could be made to lessen its environmental impact further. In this regard, the main finding of this study is that the manufacturing and production of the offshore rectennas remain as the most prominent environmental hotspot, drawing similarities to the findings of Wilson et al. (2020) [9]. This was mainly due to the significance of their size, which cover an area of 76.97 km^2 each. More specifically, the most impacting area of the rectenna manufacturing and production is the turning and casting of aluminium, the turning of steel and the transmission network. Therefore, to ensure the entire system is as sustainable as possible, the carbon footprint of the rectenna should be one of the primary design drivers. However, based on a planetary boundary perspective, impacts stemming from ozone depletion and freshwater aquatic ecotoxicity could potentially be considered as even more significant environmental hotspots, making these even more critical to address. The findings from this study will, therefore, be used to establish environmental and eco-design guidelines and requirements for the UK SEI concerning future SPS development. Ultimately, it is thought that such an approach would lead to the system being an enabler for net-zero and act as a catalyst in achieving such targets.

Despite this, it should be noted that several assumptions had to be made due to a lack of complete data. To test the net effect of these assumptions, it is recommended that uncertainty analyses are conducted in future studies based on the data quality analysis results. Uncertainty quantification is a topic which has generally not yet been addressed as part of the space LCA concept. However, a project is about to kick-off at the University of Strathclyde to address this missing element. As such, there is scope to trial the new method which is developed as part of future studies to create added value to these reports.

The next analysis may also consider extending the system boundary. In this regard, this analysis did not address the impacts of the wireless power transmission to the atmosphere, and it assumed that 100% of the energy received at the rectenna was fed into grid rather without consideration for other potential applications (e.g., storing energy as H_2 via electrolysis). For this reason, further study into other environmental issues could be considered, including energy storage potential, land use through rectenna siting and beam power density. Moreover, it is suggested that future studies might also investigate the impact of future pathways on the LCA results due decarbonisation as well as other factors such as the impact of using alternative launch vehicles and integrating the potential role of black carbon to atmospheric processes.

Finally, since the results from this LCA study are intended to be disclosed publicly, it is recommended that third-party validation of LCA results should consistently take place at appropriate points in the SEI technology roadmap, perhaps in places where the design is 'frozen' between mission life cycle phases.

Acknowledgements

The authors would like to thank Kaela Campbell (Metasat UK), Megan Campbell (Metasat UK), Katy Murphy (Metasat UK) and Erika Tonhauser (Metasat UK) for their contribution to the underlying report on which this paper is based. The authors would also like to acknowledge Ian Cash (International Electric Company), David Homfray (Satellite Applications Catapult), Paula Mills (Satellite Applications Catapult), Martin Soltau, (Frazer-Nash Consultancy), Howard Lungley (Frazer-Nash Consultancy) and Peter Entwistle (Frazer-Nash Consultancy) for their contribution and input.

Disclaimer

The report on which this paper is based was commissioned by the UK SEI and prepared by Metasat UK and the University of Strathclyde, in collaboration with the SEI Environment Working Group and SEI Technical Working Group. All of the information contained within this paper has been derived from the report, which is considered accurate (to the furthest extent possible) as of 16 June 2022 for the stated product development timeline of the SEI over the period 2022-2080. Subsequent updates and revisions to the underlying report are expected periodically since the results are highly susceptible to change due to design advancements of the SEI programme, as well as scientific updates.

REFERENCES

1. The Climate Change Act 2008 (2050 Target Amendment) Order 2019. [Online]. Available at: www.legislation.gov.uk/uksi/2019/1056/contents/made [Last accessed: 16/05/2022].
2. Shepheard, M. (2020). "UK net zero target." *Institute for Government*. [Online]. Available at: https://www.instituteforgovernment.org.uk/explainers/net-zero-target [Last accessed: 16/05/2022].
3. BEIS, (2022). "2020 UK Greenhouse Gas Emissions, Final Figures." [Online]. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1051408/2020-final-greenhouse-gas-emissions-statistical-release.pdf [Last accessed: 16/05/2022].
4. Frazer-Nash Consultancy, (2021). "Space Based Solar Power: De-risking the pathway to Net Zero." [Online]. Available at: https://www.fnc.co.uk/media/e15ing0q/frazer-nash-sbsp-executive-summary-final.pdf [Last accessed: 16/05/2022].
5. Asakura, K. et al. (2000). "CO_2 Emission from Solar Power Satellite through its Life Cycle: Comparison of Power Generation Systems Using Japanese Input-Output Tables," in: *13th International Conference on Input-Output Techniques, Macerata, Italy, 2000*.
6. Hayami, H. et al. (2005). "The Life Cycle CO_2 Emission Performance of the DOE/NASA Solar Power Satellite System: A Comparison of Alternative Power Generation Systems in Japan," *IEEE Transactions on Systems, Man, and Cybernetics – Part C: Applications and Reviews*, **35**(3), pp. 1014-1024, 2005.
7. Wilson, A.R. (2022). "Estimating the CO_2 intensity of the space sector." *Nature Astronomy*, **6**, 417-418 (2022).
8. Wilson, A. R. et al. (2021). "From life cycle assessment of space systems to environmental communication and reporting," in *72nd International Astronautical Congress (IAC), Dubai, United Arab Emirates, 2021*.
9. Wilson, A. R. et al. (2020). "A process-based life cycle sustainability assessment of the space-based solar power concept," in 71st International Astronautical Congress (IAC), The CyberSpace Edition, 2020.
10. Wilson, A. R. et al. (2022). "Life Cycle Assessment of the UK Space Energy Initiative Technology Roadmap," Technical Report, UK Space Energy Initiative, 2022.
11. Cash, I. (2019). "CASSIOPeiA - A new paradigm for space solar power." *Acta Astronautica* **159**(2019), pp. 170-178.
12. ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework, Geneva, Switzerland.
13. ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines, Geneva, Switzerland.
14. Space Energy Initiative (2022). "Space Based Solar Power." [Online]. Available at: https://spaceenergyinitiative.org.uk/space-based-solar-power/ [Last accessed: 16/05/2022].
15. ESA LCA Working Group (2016). "Space system Life Cycle Assessment (LCA) guidelines."
16. Manfredi, S. et al. (2012). "Product environmental footprint (PEF) guide," European Commission, Ispra, Italy.
17. European Commission Joint Research Centre (2018). "Product Environmental Footprint Category Rules Guidance," Version 6.3, May 2018.
18. Wilson, A. R. (2019). Advanced Methods of Life Cycle Assessment for Space Systems. PhD thesis, University of Strathclyde.
19. Wilson, A. R. (2018). ESA Life Cycle Inventory (LCI) Validation Project – Final Project Report." HIF-HO/CB/12.5/136.
20. Guinée, J. B. et al. (2002). *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Series: Eco-efficiency in industry and science*. Kluwer Academic Publishers, Dordrecht.
21. Fantke, P. et al. (2002). "Usetox®2.0 Documentation (Version 1),", 2002. [Online]. Available at: http://usetox.org [Last accessed: 16/05/2022].
22. Huijbregts, M. A. et al (2017). "ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level." *The International Journal of Life Cycle Assessment*, **22**(2), 138-147.
23. Intergovernmental Panel on Climate Change (2013). "Anthropogenic and Natural Radiative Forcing". In: *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2013.
24. Pettersen, J. B. (2019). "LCA Harmonization – final presentation" ESA, ESTSEC, 4th November 2019.
25. Chanoine, A. et al. (2022). "Environmental Expert Evaluation of ESA Space System Life Cycle Assessment Guidelines." ESA Workshop, January 27, 2022.
26. Serrano, S. S. (2021). "ESA Life Cycle Assessment (LCA) Database Usage." TN CSCE-TN-ESA-ST-0024.
27. Rockström, J. et al. (2009). "Planetary Boundaries: Exploring the Safe Operating Space for Humanity," *Ecology and Society* **14**(2): 32.
28. Sala, S. et al. (2016). "Global environmental impacts and planetary boundaries in LCA," *JRC Technical Reports*, Publications Office of the European Union, 2016.
29. United Nations Environment Programme (2021). "Addendum to the Emissions Gap Report 2021: A preliminary assessment of the impact of new or updated nationally determined contributions, other 2030 pledges and net-zero emissions pledges announced or submitted since the cut-off dates of the Emissions Gap Report 2021." [Online]. Available at: https://wedocs.unep.org/bitstream/handle/20. 500.11822/37350/AddEGR21.pdf [Last accessed: 16/05/2022].
30. BEIS (2021). "Digest of UK Energy Statistics: Annual data for UK, 2020." [Online]. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1060151/DUKES_2021_Chapters_1_to_7.pdf [Last accessed: 16/05/2022].
31. Climate Change Committee (2022). "Advice on reducing the UK's emissions." [Online]. Available at: https://www.theccc.org.uk/about/our-expertise/advice-on-reducing-the-uks-emissions/ [Last accessed: 16/05/2022].
32. BEIS (2020). "Greenhouse gas reporting: conversion factors 2020." [Online]. Available at: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020 [Last accessed: 16/05/2022].
33. United Nations Economic Commission for Europe (2021). "Life Cycle Assessment of Electricity Generation Options." [Online]. Available at: https://unece.org/sites/default/files/2022-01/LCA_final-FD_0.pdf [Last accessed: 16/05/2022].

Received 3 January 2023 **Approved** 7 March 2023