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Sustainable Re-entry Materials: Bridging the gap between Space Safety and Sustainability via the Life Cycle Assessment (LCA) of atmospheric re-entries of EEE(E) parts and energy materials

- [x] **Research & Development track**
- [ ] **Business Development track**

Abstract:

Space debris mitigation in Low Earth Orbit (LEO) increasingly relies on atmospheric re-entries and the design for demise (D4D) approach to dispose of spacecraft while avoiding ground casualties. Yet the environmental consequences of re-entries, e.g. on climate, ozone, and atmosphere, remain poorly understood. To bridge the resulting conflict of interest between space safety and sustainability, this project aims to identify materials with the least ecological damage during atmospheric demise applying the Life Cycle Assessment (LCA) method on the re-entry of energy materials and EEE(E) components.

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1. Background and problem description

Due to the risk of a Kessler collision cascade, current space safety rules require Low Earth Orbit (LEO) satellite operators to dispose their spacecraft through atmospheric re-entries [1,2]. The approach is based mainly on reducing collision risk in orbit and avoiding ground casualties. Effects of demising material in the atmosphere (e.g., chemical reactions, residence time, and consequent impact for ecosystems and humans) is not yet considered. However, in the next decade, the mass of re-entering satellites is expected to increase significantly up to 16,000 t/a [3]. Impacted environmental categories with already quantifiable damage from demise products are ecotoxicity, human toxicity, ozone depletion, and climate change [4–6]. Other potentially influenced areas include local weather, light pollution, Earth's radiation balance, troposphere damage, and particulate matter [6–10]. Therefore, the herein proposed goal to identify sustainable materials for LEO missions is extremely relevant for the future of our orbits and Earth's environment. To prevent the risk of a Kessler collision cascade and ensure safe orbital operations, space debris mitigation strategies are essential. Satellite operators rely on three disposal tactics: Lunar impact, transfer to graveyard orbits, or controlled atmospheric re-entries. The latter is the most used and often the most economically viable, especially in LEO due to atmospheric drag and the proximity to Earth. In compliance with international safety guidelines, design for demise (D4D) ensures that re-entering materials disintegrate before reaching Earth's surface, aiming to reduce the casualty risk below the 1:10,000 threshold [11]. However, this destructive disintegration of structures during re-entries presents significant yet poorly understood ecological risks. This policy and related research gap are depicted in Figure 1. An increasing amount of environmental damage categories has already been linked to re-entry emissions [3–10]. Here the key issue is uncertainty. Agencies and operators lack reliable data on the quantity and type of elementary flows into the atmosphere. This includes their physical state, particle size distribution, and consequent chemical reactions after ablation and atomisation. Nonetheless, due to their simplicity, atmospheric re-entries will remain an essential tool to dispose of space objects, especially in LEO. Therefore, ensuring that the materials used in satellites are not only demisable but also environmentally friendly regarding the aforementioned impact categories is crucial. This research proposal addresses the need to assess and recommend materials that fulfil both space safety and environmental sustainability criteria, setting the foundation for a new category: Sustainable re-entry materials.

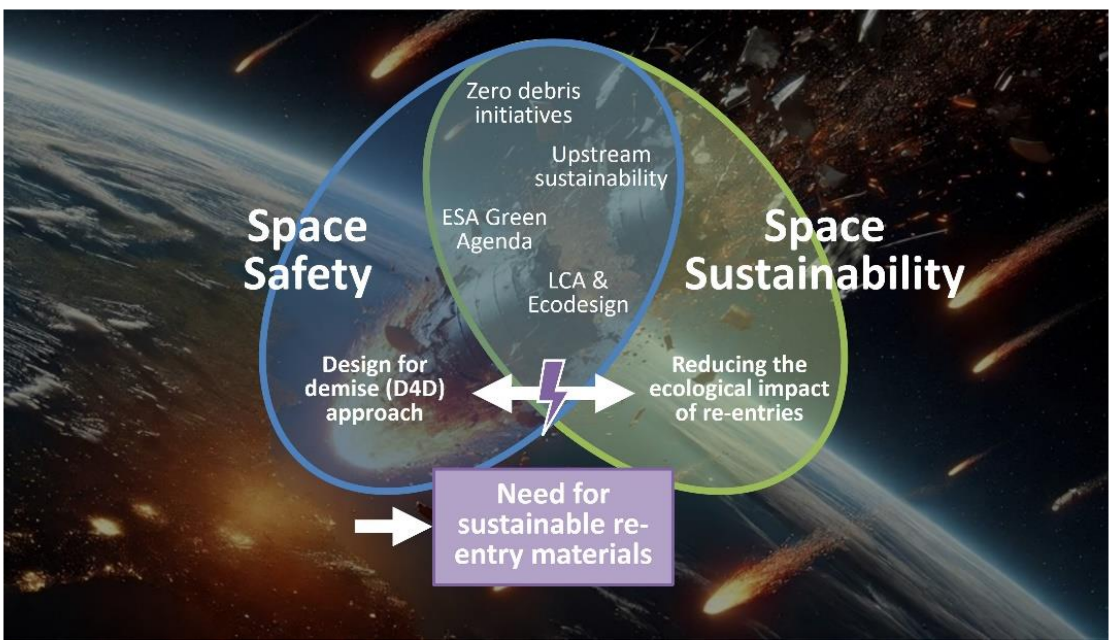

Figure 1: The need for sustainable re-entry materials: How to fill the gap between space safety and space sustainability.

2. Project idea description

The proposed research takes a new direction by shifting the focus from Space Safety alone to an integrated Space Sustainability and Safety perspective. Previous re-entry studies had the goal to improve the thermal resistance or demisability of materials. In contrast, this research will provide first time insights into the unique combination of re-entry simulations of different energy materials (used for power conversion and storage) for typical EEE(E) (electric, electronic, electromechanical, and electro-optical) parts, coupled with different in-situ and post-mortem characterisation methods to determine re-entry processes and detailed reaction products. These elementary flows are consequently modelled and evaluated with the ISO-standardised Life Cycle Assessment (LCA) method to determine the holistic environmental impact of each re-entry. So far there is no comprehensive LCA computation on EEE(E) parts including the demise. The feasibility of this approach has been recently proven in Dennis Michael Jöckel's master's thesis, a collaboration between TESAT and TU Darmstadt, where the behaviour and environmental impact of 6 selected and representative EEE(E) parts during destructive re-entries was modelled and assessed [12]. However, the herein proposed broad systemic identification of sustainable materials for LEO applications based on experimental simulations and LCAs of re-entries has never been done before.

2.1 Research objective and relevance

The central challenge of the coming decade will be closing the gap between maintaining orbital safety and avoiding environmental damage from re-entries. This project aims to develop a reproducible methodology to assess the environmental impact of typical EEE(E) parts and energy materials during atmospheric demise. This is highly relevant for multiple of the UN's Sustainable Development Goals, including SDG 3 (Good Health and Well-Being), SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), SDG 14 (Life below Water), and SDG 15 (Life on Land). ESA's Zero Debris endeavours also outline the importance of incorporating sustainability in end-of-life strategies. Chapter 6 of the Zero Debris Technical Booklet 2024, for example, addresses the importance of assessing the impact of re-entries on the atmosphere, oceans, and terrestrial environments. The project addresses this by aiming to define a viable, scalable approach to identify and quantify re-entry emissions through a combination of simulations, characterisation methods, and life cycle assessment.

2.2 Combining Life Cycle Assessment with traditional re-entry science

Life Cycle Assessment (LCA) is an ISO-standardised methodology designed to quantify the environmental impact of products and processes across four interrelated phases: (1) Goal and Scope Definition, (2) Life Cycle Inventory (LCI), (3) Life Cycle Impact Assessment (LCIA), and (4) Interpretation (compare Figure *2*) [13,14].

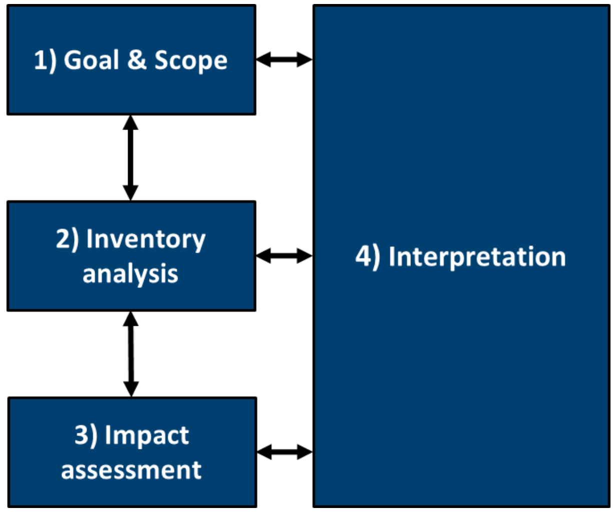

Figure 2: The LCA phases according to ISO 14040/44 [13,14].

In this research, experimental re-entry simulations provide the necessary primary data for the LCI phase, while ESA's 2025 LCA database, complemented by the Environmental Footprint (EF) method and other recent publications, enable a robust LCIA with altitude-sensitive characterisation factors for multiple impact categories of interest. The goal and scope phase defines the re-entry of selected EEE(E) and energy materials as the functional unit. The system boundaries include the re-entry process and all mass flows to the ecosphere (atmosphere, terrestrial environment, and aquatic environment) during the end-of-life of the part or material (compare Figure 3). The interpretation phase evaluates emission hotspots, limitations, and guides recommendations. This integration of LCA with re-entry and material science offers a novel pathway to evaluate the ecological consequences of spacecraft demise and informs sustainable material choices.

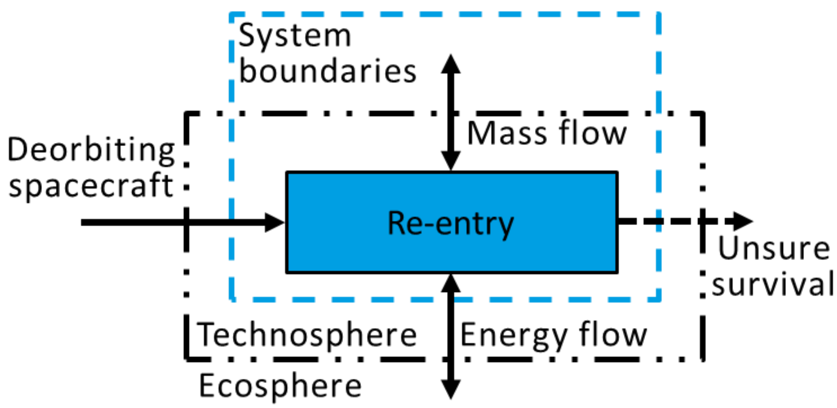

Figure 3: The investigated system boundaries are defined according to ISO standard.

3. Implementation

The implementation of the proposed approach begins with the development of a comprehensive methodology for assessing the atmospheric re-entry of various energy materials and EEE(E) parts. This methodology is established through an extensive review of the literature, integration of Life Cycle Assessment (LCA) software tools, and application of the latest European Space Agency (ESA) LCA database to model the expected elementary flows released into the atmosphere. Experimental simulations are then conducted to replicate the re-entry conditions of different EEE(E) parts and energy materials, employing combined in-situ and post-mortem characterization techniques. These include optical emission spectroscopy (OES) during plasma wind tunnel (PWT) experiments, differential thermal analysis (DTA) concurrent with thermogravimetric analysis (TGA), and post-mortem analyses such as scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), optical microscopy, and X-ray diffractometry (XRD). Subsequently, a detailed Life Cycle Assessment of the re-entry phase is performed for each part and material in accordance with ISO 14040 and ISO 14044 standards. The Life Cycle Inventory is informed by experimentally derived elementary flow data, while the Life Cycle Impact Assessment is conducted using OpenLCA software alongside the ESA LCA database, the Environmental Footprint LCIA method, and other characterisation factors from recent publications, with a consequential interpretation following ISO 14044 guidelines. This approach enables the systematic evaluation of typical EEE(E) components and energy materials to identify those with the highest and lowest environmental impacts on atmospheric emissions, ecosystems, and human health. Finally, materials with low expected environmental impact are presented, while considering their functionality and high necessary reliability for space applications. The implementation is depicted in Figure 4.

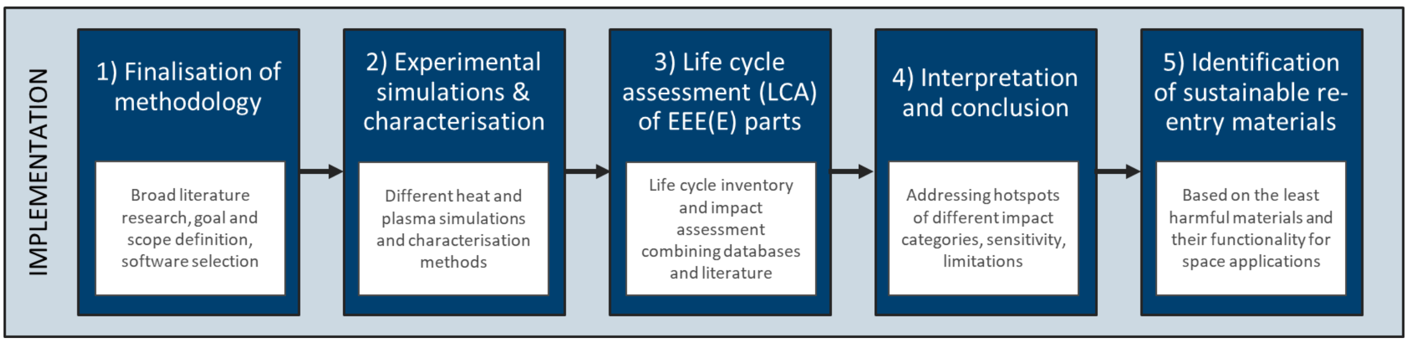

Figure 4: Methodological implementation of proposed research.

3.1 Experimental methods to capture re-entry emission data

Experimental characterisation of re-entry emissions employs a combination of in-situ and post-mortem analytical techniques (compare Figure 5 and Figure 6). In-situ optical emission spectroscopy (OES) during plasma wind tunnel experiments enables real-time identification of excited atomic and molecular species released by material ablation under simulated re-entry conditions. Concurrent differential thermal analysis (DTA) coupled with thermogravimetric analysis (TGA) provides complementary data on mass loss behaviour, chemical reactions, and thermal decomposition pathways. The possibility of combining the TGA-DTA with a gas chromatograph (GC) will also be explored. Furthermore, other low pressure plasma sources starting at 3 mbar will be added during the study. It is planned to couple these with the GC as well. All experimental data will be compared with previously reported reaction products, surface plasma interactions and particle size distributions to ensure state of the art re-entry modelling.

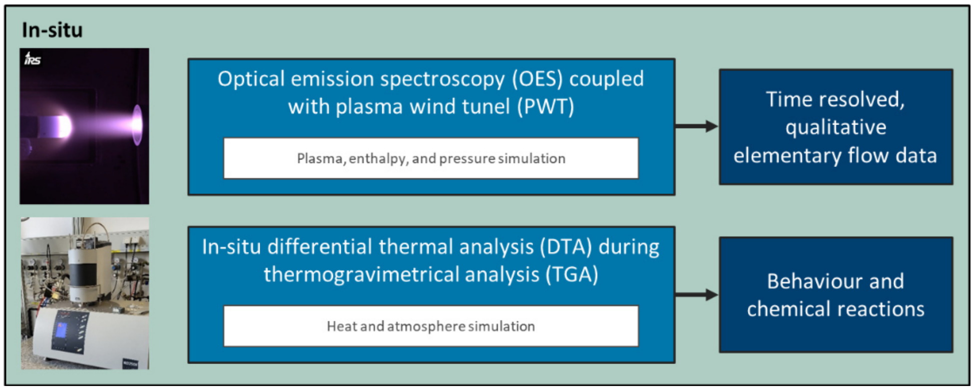

Figure 5: Experimental re-entry simulations with in-situ characterisation methods. More plasma sources will be added and it is planned to also couple the TGA with a GC.

Post-mortem analyses include optical microscopy, scanning electron microscopy combined with energy-dispersive X-ray spectroscopy (SEM-EDX), and X-ray diffractometry (XRD), which collectively characterize the morphology, surface chemistry, and crystalline phases of the residual materials following heat and plasma exposure. Future experimental campaigns will incorporate new plasma sources to replicate different additional atmospheric conditions, with an emphasis on identifying demising and surviving materials and their respective interactions with the atmosphere.

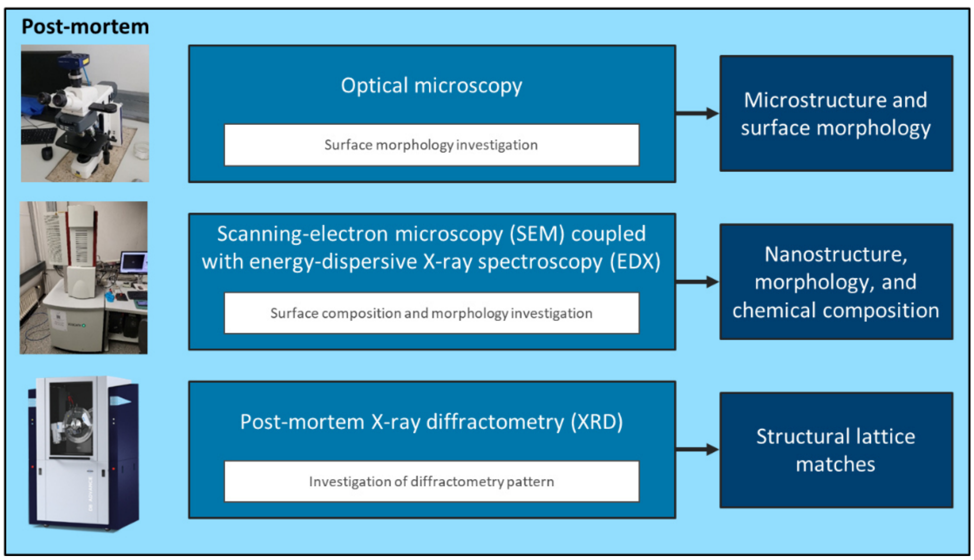

Figure 6: Post-mortem characterisation methods after PWT and TGA experiments.

3.2 Data integration and impact modelling

The elementary flows quantified via the described experimental techniques will be systematically mapped onto established Life Cycle Inventory (LCI) datasets. Leveraging ESA's LCA 2025 database, supplemented by Environmental Footprint (EF) method data and other novel publications, enables comprehensive modelling of emissions in different altitudes and environments. This multi-altitude emission impact model facilitates the assessment of key pollutant classes including greenhouse gases, ozone-depleting substances, toxic compounds, and reactive metals. Such modelling approaches are essential to estimate environmental impacts during the re-entry phase, thereby informing consequent material selection and design strategies aimed at minimizing atmospheric and ecological harm. Potential data gaps regarding characterisation factors necessary for the life cycle impact assessment will be addressed with a model that is possible to update at any given time to react to the latest publications in atmospheric chemistry. The first LCA results will be marked as "less harmful materials" because holistic multi-category sustainability assessment will only be possible when atmospheric models achieve higher altitude resolutions in the near future. Nonetheless, given the exponentially increasing re-entering mass, obtaining solid material recommendations for LEO quickly is crucial for the future of our planet and must therefore not be postponed.

4. Expected Results

The proposed research is expected to generate actionable results that directly link space safety with environmental sustainability. By applying a reproducible methodology for simulating re-entry events and quantifying their ecological impact through Life Cycle Assessment, the study will produce comparative impact profiles for key EEE(E) and energy materials (compare Figure *7*). Particular focus will be given to materials like beryllium oxide, lead solder, lithium cobalt oxides, and emerging alternatives. These results will lead to the identification of emission hotspots and environmentally critical components, providing a foundation for material substitution strategies. The outcomes will include concrete recommendations for sustainable material selection, which can inform spacecraft design processes and compliance with evolving D4D requirements. This contributes to a potential paradigm shift from a purely safety-oriented D4D approach to a sustainability-integrated strategy where material choices are optimised not only for fragmentation and ground safety but also for environmental performance during atmospheric demise. These findings will support ESA's Clean Space initiative and facilitate the implementation of the Zero Debris Charter, particularly in its call for comprehensive end-of-life assessments. Beyond institutional value, the results hold strong commercial relevance. As regulatory frameworks and market pressures, such as the EU Green Deal and ESA's LCA Data Questionnaire, drive demand for greener solutions, this project offers a ready-to-use assessment framework. TESAT's involvement ensures rapid technology transfer and industrial validation, enabling integration into their Parts Agency services. The methodology and its outputs will include an environmental materials database, validated LCA workflows, and sustainability metrics and present high commercial potential for EEE(E) suppliers, primes, and mission planners. Derived from this study tools can be integrated into LEO mission planning software, atmospheric demise simulations, and ESA-aligned sustainability reporting, opening paths for both licensable IP and consultancy services. Ultimately, the project's results will help build a safer, more sustainable orbital environment and support Europe's leadership in clean and responsible space operations.

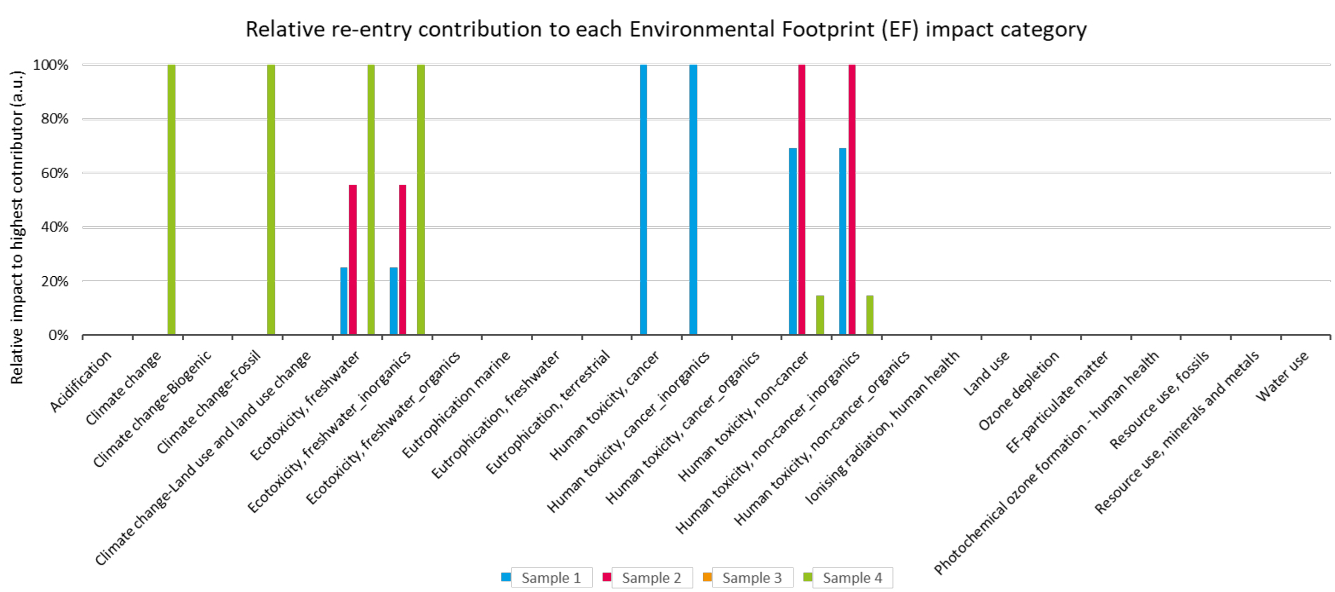

Figure 7: Relative re-entry impact from four different samples with realistic demise assumptions including emissions to lower stratosphere and upper troposphere and sea water (EF LCIA method, version 3.1 2022). The observed impact hotspots occurred from CO_2, metal (Pb, Cu, Ag) and metal oxide (NiO, SnO_2, Fe_3O_4) elementary flows amongst others. Furthermore, impacts on other categories like ozone depletion could be identified but not yet quantified due to data gaps in characterisation factors [12].

A core deliverable is a set of material recommendations for satellite designers, highlighting options with lower environmental footprints but maintained functional integrity. These guidelines will be formatted to support ESA’s Clean Space and Zero Debris initiatives. Furthermore, current D4D focuses on fragmentation and thermal breakdown. This project introduces environmental sustainability as a third metric. The goal is to transform D4D into a more selective demise strategy, integrating sustainability with safety and compliance.

5. Potential Risks

The assessment of atmospheric re-entry emissions through Life Cycle Assessment (LCA) is currently limited by several factors. First, LCA relies on accurate and comprehensive inventory data, yet ESA's LCA database lacks precise atmospheric models and high-resolution emission datasets specific to re-entry scenarios. Consequently, the project must depend on extrapolations and proxy data, introducing a degree of uncertainty that, while manageable, limits precision. This will also be addressed by the creation of a model that can be updated to react to the latest atmospheric research. Uncertainties will also be considered in the LCA’s sensitivity phases, comparing the differences in results from switching data sets, demise assumptions, impact categories, and other origins for uncertainties. Moreover, the characterisation methods applied in this study are based on controlled laboratory simulations. While these plasma and thermal tests yield valuable data, they do not fully replicate the complex and variable conditions of real atmospheric re-entries. Parameters such as re-entry angle, velocity, atmospheric density, and gas compositions can significantly influence ablation dynamics and chemical transformations. Therefore, more in-situ measurements during actual re-entries are essential to validate and refine simulation-derived findings. Finally, material recommendations based solely on environmental criteria may conflict with mission-critical performance requirements. Some low-impact materials may not meet reliability, thermal, or radiation tolerance thresholds necessary for space operations. The proposed guidelines will thus consider these constraints, balancing sustainability with functional performance to ensure applicability in real mission contexts.

6. Conclusion and Outlook

This study presents a pioneering framework to integrate Life Cycle Assessment (LCA) with re-entry and material science for evaluating the environmental sustainability of spacecraft materials. By bridging a critical policy and research gap, the proposed approach enables evidence-based material selection for re-entries and LEO missions, directly supporting ESA’s Green Agenda and Clean Space objectives. The methodology empowers designers, agencies, and manufacturers to move beyond the current safety-only paradigm of Design for Demise (D4D), incorporating ecological impacts into early-stage design decisions. Looking ahead, the implementation of sustainable re-entry materials could transform end-of-life planning into a strategy that advances both orbital safety and environmental sustainability. The framework developed in this research is scalable and can be expanded to include entire spacecraft subsystems, contributing to ESA’s internal sustainability metrics and regulatory guidance. Moreover, this initiative aligns with multiple UN Sustainable Development Goals (SDGs). In doing so, it positions ESA and its partners at the forefront of responsible space exploration and planetary protection.

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