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Beyond Debris Mitigation: Integrating Sustainability Across the Space Mission Lifecycle

Marcos Eduardo ROJAS RAMIREZ, [*]*Sophie MISSONNIER,* [†] *Antoine Jean JENDZIO-VERDASCA,* [†] *and Anissa DJAFFAR* [†]

[*] CT Engineering Group
Address 41 Boulevard Vauban immeuble Arago I
78280 Guyacourt, France
marcos.rojas@ctengineeringgroup.com - sophie.rojas@ctengineeringgroup.com
[†] Corresponding Author

Abstract

In recent years, the vision for long-term sustainability in space has expanded beyond debris mitigation. By integrating environmental responsibility across all engineering, procurement, and operational processes, sustainability is embedded into engineering processes early, setting the foundations for sustainability-driven innovation in the space sector. This paper discusses how sustainability principles can be integrated into the design of space systems, using the INSIDeR project as a case study. It also highlights the potential of eco-design, circular economy strategies, and lifecycle assessment (LCA) as essential tools for creating a truly sustainable space industry that is technically feasible and economically viable.

1. Introduction

Today, sustainability in space has evolved into a broader recognition that every phase of a space mission, from early design choices to final disposal, carries environmental, economic, and social implications. The increasing scale of global space activities has highlighted that long-term viability relies on our ability to implement sustainable practices in the design, construction, operation, and retirement of space systems [1]. This section outlines the evolution of the sustainability discourse, highlights how Europe is responding through concrete frameworks, and outlines the intent of this paper to contribute to this conversation.

1.1 Rethinking Space Sustainability

Until recently, sustainability in space was primarily associated with orbital safety: debris mitigation, collision avoidance, passivation, and end-of-life planning. While these measures remain essential, they no longer capture the full scope of what sustainability requires. As space activities expand, the environmental footprint of space systems now includes upstream emissions, material sourcing, manufacturing practices, supply chain behaviour, and energy use on Earth and in orbit [2]. Such evolution reflects a growing understanding that space systems are part of a broader ecosystem that affects and is affected by sustainable development goals [1][3]. Therefore, a sustainable space sector must address both operational risks and lifecycle impact. It must also consider how space systems contribute to or hinder sustainability on Earth. These concerns are driving efforts to develop a new generation of practices focused on resource efficiency, cleaner design, and greater alignment with long-term societal goals.

1.2 The European Perspective

Europe has taken a leading role in expanding the definition of space sustainability through formal programmes and design frameworks. ESA's Green Agenda and Clean Space Initiative explicitly frame sustainability as an integrated design objective supported by lifecycle assessment tools, implementation guidelines, and evolving procurement requirements [2][4]. In addition, various efforts at the national level, such as CNES's RSE strategy, all place environmental responsibility at the centre of mission planning, going beyond compliance and integrating sustainability into design methods, material selection, supplier engagement, and system verification [5].

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Its focus on practical implementation sets the European approach apart, which helps projects translate high-level goals into day-to-day design choices. This strategy elevates Europe's technical credibility and strengthens its ability to shape international standards through initiatives such as the Zero Debris Charter [6].

1.3 Objective and Scope of the Paper

This paper explores how sustainability can be integrated early in the development of space systems. It uses the INSIDeR project as a case study to examine how environmental responsibility can shape design architecture, sourcing decisions, and system integration. Beyond this technical example, the paper will also elaborate on the broader frameworks and concrete tools that guide the implementation of sustainable engineering in space projects in Europe.

2. Embedding Sustainability in Space System Design

Sustainability in space is no longer limited to regulatory compliance or post-mission considerations. Increasingly, it is recognised as a design driver with strategic implications. Embedding sustainability into space systems requires that environmental responsibility be considered from the start, not only at the end of a mission's life. This section explains why sustainability is becoming a fundamental design consideration, how environmental impacts arise throughout the mission lifecycle, and why we must shift from merely mitigating effects to fully integrating sustainability across the entire mission lifecycle.

2.1 Environmental Responsibility as a Design Driver

Environmental sustainability has introduced a new dimension to system optimisation, complementing mass, cost, performance, and risk in early-phase decision-making. Traditionally, sustainability has been viewed as a constraint, often considered only after making key design decisions. However, the European Space Agency's (ESA) Green Agenda and Strategy 2040 now place environmental responsibility at the forefront of project governance, making it a strategic and programmatic priority [2][7]. ESA has committed to reducing greenhouse gas emissions by 46% from its internal operations and 28% across supplier activities by 2030 [7]. These targets are supported by a systemic shift: sustainability maturity frameworks, simplified life cycle assessment (LCA) tools, and mandatory eco-design criteria are being developed and implemented across all directorates [8]. Consequently, ESA envisions a transition towards a "Green and Sustainable Space," where sustainability is integrated from mission conception to disposal and throughout the entire space economy [7]. In this evolving landscape, systems incorporating sustainability from the beginning are technically sound and strategically advantageous. They align with funding priorities under the CM25 framework, procurement reforms, and ESA's long-term investment vision, making environmental responsibility a basis for relevance, credibility, and programmatic compatibility in the coming decades.

2.2 Mission Lifecycle and Environmental Impact

The environmental impact of space systems accumulates throughout the entire mission lifecycle, from material extraction and component manufacturing to launch, operations, and deorbitation. The European Space Agency's (ESA) updated Life Cycle Assessment (LCA) methodology broadens this scope to include infrastructure use, testing campaigns, and indirect activities such as facility energy consumption and office-based design work [8]. Notably, more than two-thirds of ESA's current greenhouse gas (GHG) emissions are associated with space systems, particularly through upstream supply chains [8]. By assessing the impact across greenhouse gases, resource depletion, eco- and human toxicity, and more, ESA transforms sustainability from a single environmental metric into a system-level performance quality that spans disciplines, suppliers, and mission phases [8]. This comprehensive approach demands that teams view environmental responsibility not as an isolated task but as a continuous variable in engineering decisions.

Mapping these impacts to key phases allows mission teams to identify hotspots and make informed trade-offs:

- **Design and Manufacturing**: Supplier selection, material traceability, and production energy intensity
- **Launch**: Vehicle emissions, secondary payload integration, propellant footprint
- **Operations**: Power demand, data transmission loads, autonomous operation requirements
- **Testing and Qualification**: Redundant hardware, thermal-vacuum cycles, facility usage, reuse of test models
- **End-of-Life**: Disposal strategy, reentry fragmentation, residual collision risk

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ESA's Strategy 2040 pictures a future space economy prioritising material reuse, waste reduction, and minimising environmental impact both in orbit and on Earth [7]. This vision will require a much higher awareness and commitment to trace upstream and downstream decisions and their impact across the entire mission lifecycle.

2.3 From Mitigation to Integration

Sustainability in space has traditionally focused on reducing orbital risks. However, the scope of sustainability today extends to the space sector's broader environmental footprint on Earth, from launch emissions and manufacturing processes to supply chain logistics and ground infrastructure [9]. ESA has formalised this change by incorporating eco-design and lifecycle thinking as essential components in procurement and mission definition [7]. ESA's Strategy 2040 explicitly states that sustainability criteria will be applied systematically [7]. As a result, procurement processes will evolve to favour projects that demonstrate a reduced environmental footprint and show genuine contributions to environmental stewardship and societal value. The following section will present the INSIDeR project as a case study for implementing ESA's Clean Space and Green Agenda principles through early-phase considerations and design choices such as supply chain localisation, subsystem modularity, and interface simplicity. By doing so, the paper intends to use INSIDeR as an example of this shift toward space projects that promote a more sustainable orbital environment from the ground up.

3. Case Study: The INSIDeR Project

The INSIDeR (Innovative Net & Space Inflatable Structure for Debris Removal) project represents a promising approach to integrating sustainability into space system design. Designed as a modular, host-integrated ADR payload, INSIDeR offers a variety of viable pathways to incorporate environmental responsibility into its architecture. This section explores INSIDeR as a technical solution and an early case study in sustainability-focused space engineering based on clean and eco-friendly space principles established by the ESA [4].

3.1 Project Overview

INSIDeR is a compact deorbitation kit designed to be integrated into several hosting platforms, including satellites, in-orbit servicing vehicles, and launcher upper stages. It comprises an inflatable structure that deploys a net to envelop a piece of orbital debris. Once secured, the debris is towed using a tether system, relying on the host platform's propulsion to execute the deorbit manoeuvre. This solution aims to simplify ADR by eliminating the need for a specialised deorbiting vehicle. Instead, it proposes ADR as a functionality integrated through the INSIDeR system. This approach fosters sustainability by reusing existing space assets, making ADR a complementary capability implemented at the end of the host's primary mission.The ADR mission concept using INSIDeR is structured into four operational phases:

1. **Identification and Approach** – locating and manoeuvring toward the target.
2. **Debris Characterisation** – analysing the debris dynamics to confirm safe capture conditions.
3. **Capture** – deploying the net and securing the debris.
4. **Deorbitation** – removing the debris via controlled reentry or transfer to a disposal orbit.

The first stage of development for this project includes a series of ground-based structural tests, a ZeroG parabolic flight test of the deployment mechanism, and two in-orbit demonstrations (IODs) to demonstrate technical maturity. In contrast, the second stage will focus on deploying INSIDeR through its use to remove existing orbital debris.

3.2 Sustainable Engineering Practices

INSIDeR's development aligns with international debris mitigation guidelines while opening viable pathways to embed broader sustainability considerations into its architecture. Although it is still in the early stages of development, various architectural choices and design trade-offs are actively being considered, which could enable INSIDeR to model a development path that is more conscious of sustainability.

1. **European Supply Chain Localisation**: Current development has favoured European suppliers across subsystems, which may evolve into a strategic commitment supporting REACH-informed sourcing, reducing transportation emissions, and lifecycle traceability. If formalised, this path would align INSIDeR with the Clean Space objective of improving environmental performance through procurement [10].

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2. **Eco-Design Opportunities in Material and Subsystem Design**: INSIDeR's inflatable structure and net are made of materials with low mass and high demisability. These could be further evaluated through Life Cycle Assessment (LCA) methods, as promoted by ESA's eco-design toolkit, to assess environmental impact from fabrication to disposal [8]. Other options under review include design-for-demise configurations and minimising bonded assemblies to improve end-of-life performance.
3. **Configurable Architecture Based on Host Capabilities**: The kit is designed with modularity in mind. Key subsystems, such as the power supply, debris detection sensors, and data handling components, can be removed based on the capabilities of the host platform. This flexibility allows for developing leaner, more energy-efficient, and lightweight INSIDeR variants, reducing redundant system functions and optimising future configurations. As a result, different integration profiles that reinforce reuse can be established [11].
4. **Lean Verification Strategy and Demonstration Planning**: INSIDeR's IOD campaigns are being planned around launch windows based on host opportunities rather than dedicated launches. This demonstration approach could reduce emissions associated with system testing and validation. ESA's Clean Space methodology encourages such design-phase decisions, where environmental performance is optimised in the end product and across the verification process [8].
5. **Sustainability Self-Assessment and Maturity Tracking**: In parallel, INSIDeR could adopt a lightweight internal benchmarking process based on ESA's Sustainability Maturity Assessment (SMA), evaluating design decisions against five key areas: local sourcing, end-of-life demisability, reuse of host infrastructure, subsystem redundancy avoidance, and responsible packaging for launch [8]. This approach would enable proactive alignment with future sustainability metrics by identifying where INSIDeR already aligns with ESA's Green Agenda [2].

While there are several decisions to be made about the development roadmap for INSIDeR, the identified paths offer encouraging insights, highlighting its potential as a testbed for the early adoption of the Clean Space framework [12].

3.3 Operational Sustainability Through Integration

INSIDeR's architecture is grounded in minimising the need for new mission-specific infrastructure. Rather than operating as a standalone spacecraft with dedicated launch, operations, and disposal support, INSIDeR offers a solution that leverages existing infrastructure, supplying complementary capabilities to pre-existing launch services, orbital platforms, and operational timelines. This strategy reduces both the cost and environmental impact of orbital access.

By building on already-deployed systems and ongoing missions, INSIDeR transforms retiring assets and prior investments into debris removal enablers without requiring additional orbital infrastructure development. Moreover, by embedding debris removal as a complementary objective within larger space missions, INSIDeR supports a shift toward service-oriented orbital infrastructure. Rather than viewing ADR as a standalone obligation, this model empowers platform developers and mission operators to take shared responsibility for the safe and sustainable use of space. This approach intends to extend sustainability beyond engineering design, contributing to a more resource-efficient mission lifecycle and fostering a long-term transition in which orbital sustainability becomes a standard quality of how we use, extend, and retire space infrastructure [11].

3.4 INSIDeR’s Dual Role

INSIDeR aims to serve as a case study of how sustainability considerations can be introduced early in system design and carried through to integration, operations, and disposal. Its architecture emphasises low-impact, host-agnostic deployment with opportunities for lean sourcing, shared resources, and responsible material selection.

In alignment with ESA's Clean Space initiative and their Zero Debris vision [6], INSIDeR offers a development path that could:

- Support early-phase eco-design scoring and lifecycle assessments
- Demonstrate host-integrated deorbiting through the reuse of existing space hardware
- Show that sustainability requirements can be met without compromising feasibility or cost efficiency

By taking concrete steps in this direction, INSIDeR could establish a foundation for demonstrating compliance with sustainability metrics and the feasibility of multi-purpose mission campaigns. Ultimately, INSIDeR has the potential to serve as a practical tool for reducing orbital debris and as a proof of concept for how space actors can integrate sustainability into every phase of the space mission lifecycle.

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4. Broader Frameworks for Sustainable Innovation

Sustainable innovation is becoming an imperative design principle supported by formal frameworks, evolving procurement processes, and increasingly quantified environmental impact objectives. ESA's Green Agenda, Clean Space Initiative, and Technology Vision 2040 emphasise that sustainability must move from end-of-life planning to early-phase engineering and from individual compliance efforts to system-level innovation [2][4][11]. Three frameworks are currently shaping the integration of sustainability into future space systems: circular economy thinking, eco-design principles, and life cycle assessment (LCA). While each framework operates at a different scale and maturity level, they all converge in underlining the importance of early integration, traceability, and minimising impacts at every development stage of a space mission. These frameworks provide a practical foundation for sustainable engineering applied to space and will directly influence the development plan of INSIDeR in the future.

4.1 Circular Economy in Space Systems

ESA's Clean Space Initiative and Technology Vision 2040 recognise the circular economy as an essential element of orbital sustainability [4][11]. Instead of viewing space assets as disposable, the circular model emphasises reusability, reconfiguration, and resource optimisation. ESA outlined various motivations for this strategy, including environmental protection, reduced mission costs, improved reliability, and fewer launches or reentries, directly aligning sustainability with operational and economic value. In space systems, circularity may take several forms:

- **Reusability**: Components, structures, and propulsion elements that serve across multiple missions.
- **Modularity**: Payload kits or service functions compatible with several platforms.
- **Multi-functionality**: Embedding additional capabilities, like ADR or inspection, into space assets.
- **Infrastructure alignment**: Optimising the usage of existing launch, ground, and telemetry infrastructure

ESA identified several enablers critical to this transition, including standardised mechanical and data interfaces, in-orbit reliability of modular subsystems, and verification methodologies that reduce the cost and risk of reuse [10]. The vision for INSIDeR already aligns closely with these priorities thanks to its modular design for easy integration across various host systems and flexibility to fit into several kinds of mission configurations. In addition, INSIDeR facilitates debris removal while minimising the need for dedicated spacecraft, launches, and operational infrastructure. Such qualities help this project turn orbital sustainability into a comprehensive opportunity to expand the concept of reuse from payloads to the entire mission architecture. Similarly, such alignment makes INSIDeR an early and credible example of the innovation required to build a functioning circular economy in space.

4.2 Eco-Design Principles

As the foundational methodology for ESA's Clean Space programme, eco-design shifts the focus from end-of-life compliance to early-phase decision-making to reduce environmental impact across the mission lifecycle without compromising performance or reliability [4][13]. ESA's view of eco-design as a strategic enabler will be reflected within its broader programmatic logic through its proactive integration in its procurement process, which will ultimately favour solutions that implement eco-design principles, not only for environmental compliance but also for cost control, risk reduction, and strategic alignment. ESA implements eco-design through structured design guidelines, specific analyses, and scoring tools. This approach includes trade-offs, hazardous material substitution, part count reduction, supplier traceability, and disassembly-oriented assembly strategies [8]. Key practices include:

- **Material selection**: Prioritising REACH-compliant, demisable, low-toxicity materials
- **Interface design**: Allowing modular, lightweight connections that minimise redundant subsystems
- **Subsystem Optimisation**: Minimising mass, power consumption, and bonded components
- **Supplier choices**: Determining localised, traceable supply chains with lower logistical impact
- **Verification logic**: Planning lean test campaigns to reduce facility emissions and operational load

INSIDeR's design and development plan reflects many of these principles through its use of low-mass, highly demisable materials, subsystem modularity, and emphasis on interface simplicity. Its lean verification campaign minimises test facility use, and its current supplier base is primarily European. While formal scoring has yet to be applied, the project structure offers a clear opportunity to pilot eco-design assessments aligned with ESA's evolving Sustainability Maturity Assessment (SMA) framework [14].

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4.3 Lifecycle Assessment (LCA) and Decision-Making

Environmental Life Cycle Assessment (LCA) is becoming an essential tool for evaluating and comparing the environmental impact of space missions. ESA has been the primary institutional driver of LCA adoption in the space sector, adapting ISO 14040/44 standards to accommodate the specificities of low-volume, high-performance space systems [14]. These include stringent reliability requirements, mass sensitivities, unique testing campaigns, and emissions into all layers of the atmosphere. One study outlined the key challenges for LCA in this context:

- Defining appropriate **functional units** for mission comparison (e.g., "per deorbited object")
- Access to environmental data during early design phases
- Integration into classical engineering workflows
- Avoidance of burden shifting between mission phases or subsystems

ESA encourages using **simplified variations of LCA** in early project phases to address these challenges and help mission teams identify high-impact design decisions without requiring complete environmental datasets [8][14]. When combined with eco-design practices, simplified LCA becomes a powerful design aid that supports material trade-offs, supplier evaluation, and end-of-life strategy refinement. INSIDeR is well-suited for early-phase LCA applications, as it offers a fixed mission profile, specific integration configurations, and well-defined functions. The development team could adopt a simplified LCA approach to:

- Benchmark different material and subsystem options
- Evaluate emissions tied to logistics and integration
- Define measurable indicators for ADR effectiveness per kilogram captured or per orbit de-risked

This level of benchmarking would support alignment with ESA's Clean Space eco-design criteria and, more broadly, help validate the feasibility of sustainability-driven design for low-TRL systems [8][14].

4.4 Towards a Sustainable Space Industry

While INSIDeR provides a practical testbed for implementing environmental responsibility into system design, pushing toward a sustainable space industry will require broader institutional, industrial, and cultural alignment through collective adjustments in development processes, regulatory frameworks, and engineering practices across public and private sectors [9]. The benefits of early-phase sustainability integration could be quite significant. Projects that use eco-design and circular economy principles may deliver more efficient solutions with fewer costs, faster development, and enhanced suitability to modern space missions with evolving programmatic criteria. In parallel, funders, investors, and mission partners will increasingly value environmentally traceable projects seeking compliance with broader sustainability mandates. However, achieving these benefits will require early and genuine investment and commitment to integrate these practices across the entire mission lifecycle.

Space agencies and governments play a critical role in establishing sustainability standards and incentives. However, close collaboration with the industry is essential to ensure effective implementation through elegant design, clean manufacturing, and responsible supply chains. Only through joint leadership can sustainability scale beyond isolated examples. Concepts such as modularity, reusability, and lifecycle accounting must become standard terminology across technical domains and among all stakeholders. Additionally, the momentum behind sustainability in space offers a remarkable opportunity for the space sector to champion sustainability efforts on Earth by aligning engineering practices with strategic and societal goals [15].

Unfortunately, fragmented regulations and supply chains, limited access to environmental data, short-term financial constraints, and inconsistent ESG frameworks continue to hinder progress [9]. Many small or emerging space actors lack clear guidance on sustainability expectations and reporting methods. Additionally, geopolitical disruptions and economic volatility pose significant challenges for the industry regarding long-term planning, limiting their ability to implement sustainable strategies effectively. Such issues underscore a need for standardised metrics, coordinated procurement frameworks, and meaningful collaboration efforts between established and emerging space actors to overcome these barriers. Ultimately, Space Sustainability is an evolving practice grounded in engineering, policy, and governance. As the environmental, economic, and social implications of space activities grow, so too does the need for consistent, practical, and inclusive approaches.

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The frameworks outlined in this paper, circular economy thinking, eco-design, and lifecycle assessment, offer a starting point and path forward to integrate sustainability early, iterate responsibly, and design space systems for performance and long-term viability on Earth and in orbit. As the intersection between the space sector and the UN Sustainable Development Goals becomes more visible, sustainability will become a fundamental element for developing and maintaining a robust and thriving space economy [3][9].

5. Conclusion

Sustainability in space begins with engineering decisions. When considered from the earliest phases of system development, environmental responsibility can be incorporated without compromising technical feasibility, economic viability, or mission reliability. This paper presented a perspective on how sustainability principles can be progressively integrated into space system design, using the INSIDeR project as a representative case study. Although still in the early stages of development, the project offers viable pathways that reflect current priorities under ESA's Clean Space Initiative, Green Agenda, and Technology Vision 2040 through modularity, supply chain localisation, and lean verification. The future application of circular economy principles, eco-design strategies, and simplified life cycle assessment could further illustrate how to manage sustainability as a continuous design parameter rather than a mission constraint.

More broadly, the paper reflects a sector-wide shift from viewing sustainability as an obligation to treating it as a core engineering requirement. While challenges remain, the frameworks discussed here offer practical steps for anticipating future expectations and facilitating responsible engineering practices. Europe is already leading this transition, redefining how sustainability is monitored and managed through clear targets, supplier expectations, and integrated design practices. These tools and the commitment to apply them will determine whether sustainability becomes a standard of excellence or a missed opportunity to build more efficient systems, low-impact services, and more responsible policies. A sustainability-driven space sector is not only viable but necessary. As the space economy grows and the pressure on shared orbital resources increases, embedding sustainability into the foundations of mission development will enable the space sector to take practical, measurable steps toward long-term viability without compromising feasibility, reliability, or ambition.

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