GREENSAT: EXECUTIVE SUMMARY REPORT

Written by	***Responsibility*** + handwritten signature if no electronic workflow tool
GreenSat Consortium	
Verified by	
Nicolas Thiry	
Pierre-Alexis Duvernois	
Approved by	
Bernard Charlot	

Approval evidence is kept within the documentation management system.

CHANGE RECORDS

ISSUE	DATE	§ CHANGE RECORDS	AUTHOR
1.0	26/02/2019	First Issue	GreenSat Consortium

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1. EXECUTIVE SUMMARY

Resulting from an ever increasing public pressure, the quest to be environmentally friendly is transforming the competitive landscape, as eco-friendly design turns into a new frontier of innovation. As a public sector intergovernmental organisation, ESA is committed to prioritizing environmental concerns in all its activities. Through its Clean Space initiative, it is pioneering an eco-friendly approach to space activities. ESA missioned in 2016 a consortium led by Thales Alenia Space with Deloitte Sustainability to investigate the potential of the Ecodesign methodology at the scale of a space mission.

For Thales, health and safety and protecting the environment are basic principles that form part of the Group's broader commitment to creating a safer world. In the early 2000s, the Group adopted a proactive HSE policy for all of its sites, activities and products, at every level of the organisation.

Deloitte has accompanied many private and public organisations over the years in the integration of sustainability metrics in their strategy to improve the environmental performance of their products. In particular, Deloitte has capitalised over the years on its eco-design and Life Cycle Assessment (LCA) expertise applied to the space sector for this project.

The concept put forward by the consortium illustrates this complementary vision by succesfully reducing the impact on people and the environment while adding value in comparison with its reference mission (Sentinel 3). This project illustrates the potential of Eco-Design in turning the threat of environmental challenges into innovation opportunities for the space sector. In line with the study requirements and in order to support the ESA cleanspace challenges, the following priorities have been taken into account during the GreenSat project:

- **Reduced footprint on the terrestrial ecosphere:** While space may be a low-volume industry when compared to other terrestrial industries (for instance, there are millions more cars produced each year than there are satellite), reaching for the skies leaves footprint on the ground and in the atmosphere. Clean technologies for space shall be understood as those which contribute to the reduction of the environmental impact of space programmes, taking into account the overall life-cycle and the management of residual waste and pollution resulting from space activities. The LCA of Sentinel 3 mission performed by Deloitte allowed to identify "environmental hotspots": activities that carry significant environmental impacts on one or several environmental impact categories in perspective with the impacts generated during the whole life cycle of the space mission. Among the hotspots found were the use of germanium as a substrate for solar cells, energy consumption related to office work on ground during design stage and routine stage, use of CFC-emitting materials in the harness, the use of electronics in various parts of the spacecraft which manufacturing stage is resource-intensive, etc. In addition, a qualitative approach was also adopted to identify REACH and Critical Raw Materials (CRM) hotspots with the potential obsolescence risk they bring.

- **Space Debris Mitigation (SDM):** On top of mitigating the impact from space activities on the terrestrial ecosphere, sustainability in the space sector also implies to preserve the Earth's orbital environment as a safe zone, free of debris. With a current rate of 70–90 launches a year, with an increasing number of these launches injecting 30 or more small satellites into orbit at once, and assuming future break-ups will continue according to mean historical rates of four to five per year, the number of objects in space is expected to increase steadily and, with it, the probability of catastrophic collisions. In the long term, strong compliance with Space Debris Mitigation requirements is the most effective mean of stabilising the space debris environment at a safe level but it has a significant impact on LEO platform design. Compliance to SDM requirements includes in particular anticipating and avoiding collisions during the mission lifetime, disposal manoeuver to remove the spacecraft from the protected region at the end of its life, and spacecraft passivation in the case of an uncontrolled re-entry.

- **Performance and cost of the concept:** To be technically and economically viable, the solution shall demonstrate a minimum impact in term of cost and performance at satellite level. Ideally, the impacts shall be positive to justify switching from established and proven solutions. This priority is consistent with the Eco-Design approach which ESA proposed for the GreenSat project and which, according to the official definition by ADEME, "is an innovative approach aiming to reduce the negative impacts of a product/service over the course of its lifecycle, while preserving its useful qualities".

- **Maturity of the solutions:** The decision to proceed with the industrial implementation during a space programme constitutes a major decision, generally irreversible, and represents a heavy financial commitment carrying its inherent risks for ESA and for the Participating States. Quite understandably, ESA programme managers are generally opposed to the inclusion of unproven technologies on a space mission unless it is essential to fulfil the mission requirements. Thus, to be included on future ESA missions, Eco-Design solutions shall demonstrate a sufficient level of maturity. Nowadays, ESA projects typically consider a TRL 6 as the minimum threshold to move to the implementation phase.

Through the use of ultrathin ELO cells within an innovative flexible array structure, a decentralized avionics with µ-nodes, and Green Propellant, GreenSat will allow ESA to promote durable improvements on each of these points, leading to:

- **Reduction of the environmental footprint** of future space missions on several indicators without increase on the others
- **Facilitate** the **compliance** of future space missions with respect to **SDM requirements** by phasing out Hydrazine in favor of LMP-103S (High Performance Green Propellant)
- **Improvements** in the **performance and cost** of its future missions

To help ESA adopting these Eco-Design solutions on its future projects, development roadmaps have been proposed to raise the TRL of these solutions.

By allocating the appropriate effort and resources, ESA can turn these solutions into assets for its future missions and demonstrate to its ESA programme managers that they will not add constrains on the budget and programmatic aspects.

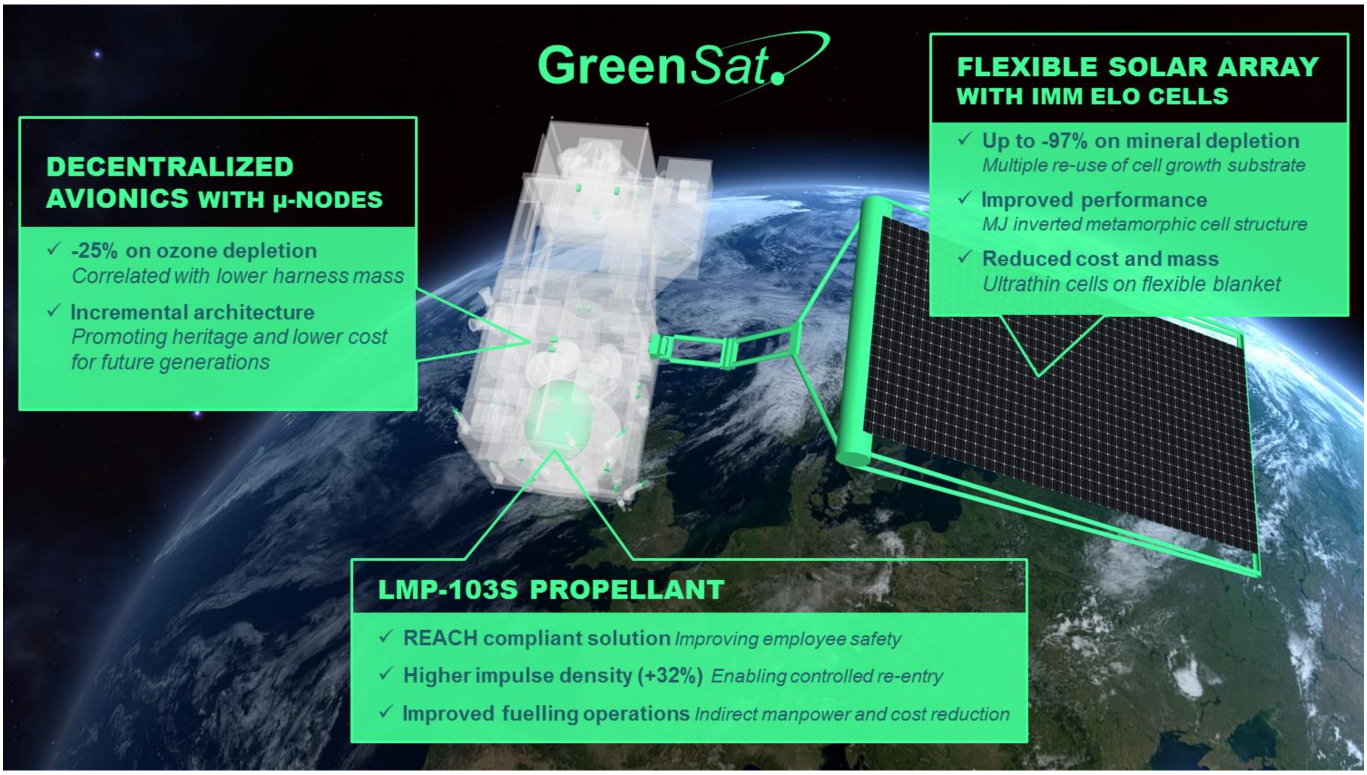


Figure 1-1: Artist vision of GreenSat concept, based on the original Sentinel 3 satellite re-designed with the 3 Eco-Design solutions.

ESA can turn the threat of environmental challenges into innovation opportunities for the European space sector by promoting the development of the GreenSat Eco-Design solutions.

2. REDUCED FOOTPRINT ON THE TERRESTRIAL ECOSPHERE

> *The GreenSat Eco-Design solutions will permit a meaningful reduction of the environmental footprint of space mission while mitigating the obsolescence risk induced by anticipated evolutions of the environmental regulations.*

The analysis of the lifecycle of the Sentinel 3 missions highlighted the contribution of the solar cells and harness to the mineral depletion and ozone depletion indicators respectively.

- **For solar cells**, the main contributor is the **Germanium** substrate, which is part of the European Commision's Critical Raw Material list. The **Epitaxial Lift-off (ELO)** method would allow to recycle this expensive Germanium wafer after growing the active layers on the solar cells. During the ELO cell growth, a release layer is deposited directly on top of the substrate, and multi-junction solar cells are then deposited on the release layer. The presence of the release layer permits the solar cell epitaxial structure to be removed from the substrate without damage. After growth the metallization of the top side of the cell is made and the cell can be placed on a thin substrate. The amount of times the substrate can be recycled is between 5-20 with chemico-mechanical-polishing (CMP) methods and more than 100 with wet chemical etching methods.

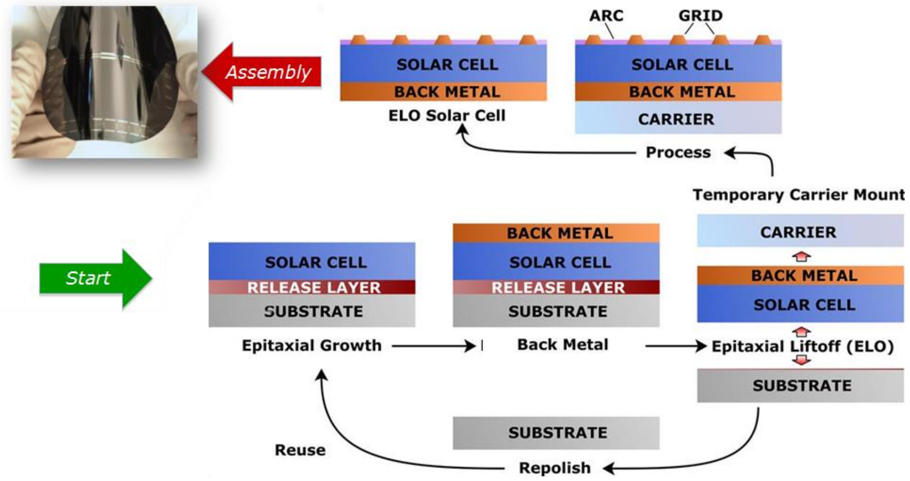


Figure 2-1: ELO method (image: Microlink)

- **For the harness**, the main contributor is **Teflon** used in cable coatings. A **decentralized avionics (DA)** architecture would tackle this hotspot by reducing the total length of cables running across the satellite. The main idea of a decentralized avionics architecture is to distribute the RTU function (embedded within the SMU on Sentinel 3) over several µ-nodes that are placed close to the equipment they serve, hereby reducing the length of dedicated cabling(up to 67% in some R&D projects).

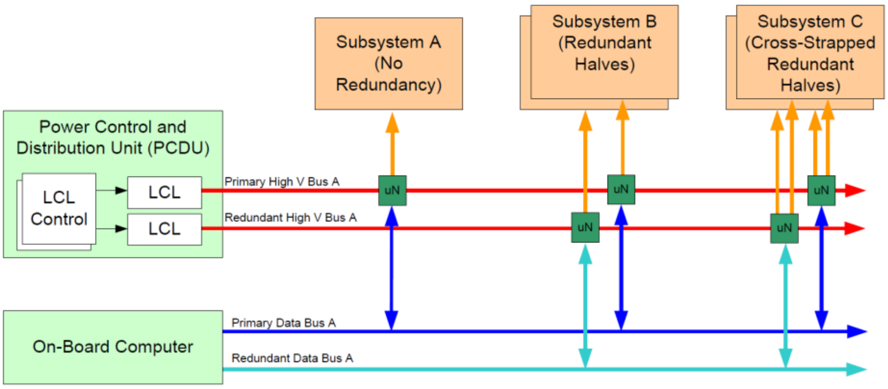


Figure 2-2: Decentralized avionics architecture concept

In addition to these, the proposed replacement of Hydrazine by Green Propellant (GP) would promote human health and safety while also anticipating the risk of obsolescence linked with the inclusion of Hydrazine in the REACH candidate list. Figure 2-3 summarizes the overall improvement of GreenSat versus the original Sentinel 3 baseline.

Figure 2-3: Breakdown of environmental impacts of the 3 Eco-Design options showing large benefits when compared to the baseline

ESA will significantly improve the environmental footprint by implementing the proposed solutions on its GreenSat.

3. SPACE DEBRIS MITIGATION

> *ESA missions requiring a controlled re-entry will benefit from a more compact propulsion subsystem architecture thanks to the higher impulse density of LMP-103S.*

Compliance of future LEO missions to Space Debris Mitigation (SDM) requirements will become a major driver in satellite architecture design. In particular, the choice of a controlled re-entry over an uncontrolled re-entry is driven by the casualty risk during the re-entry (<1E-4) which depends on satellite demisability and population densities.

Projected increase in propulation densities likely mean that, in the future, more and more missions will need to retain a controlled de-orbitation strategy. Such missions will need a higher propellant mass to cope with the additional disposal maneuver. As illustrated on Figure 3-1, the higher propellant density and performance of LMP-103S allows a more compact propulsion subsystem architectures, thus mitigating the impact on the satellite when a controlled re-entry solution is preferred.

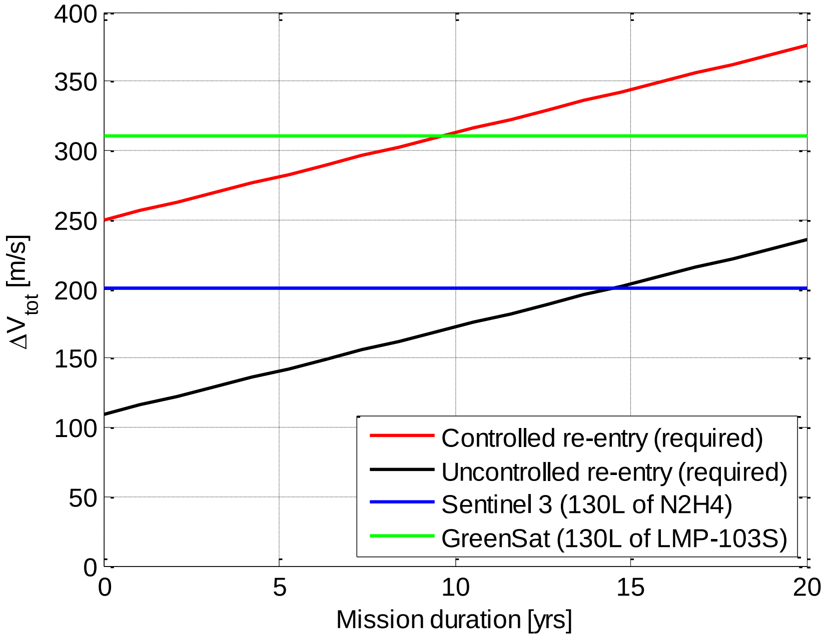


Figure 3-1 : ΔV capability of the Sentinel 3 and GreenSat missions versus total ΔV needed by the missions depending on the re-entry strategy.

ESA could simultaneouly mitigate REACH obsolescence risk and improve compliance to future SDM requirements by phasing out Hydrazine in favor of High Performance Green Propellant (LMP-103S)

4. PERFORMANCE AND COST OF THE CONCEPT

> *ESA missions implementing the selected Eco-Design option will outperform the ones that do not without increasing their recurring cost.*

On top of reducing the footprint of future space missions on the terrestrial and orbital ecospheres, the proposed solution bear the potential to durably improve the performance of future space missions:

- **ELO cells :** Recycling the substrate does not only benefit the environment. For a typical triple junction solar cell, this substrate indeed represents about 40% of the solar cell cost and more than 90% of its mass. Thus, re-using this substrate and replacing it by a cheap flexible carrier provides a clear route to reduce the mass and cost of future cells.

- **Decentralized avionics :** on top of reducing the harness mass, the development of a distributed avionics will benefit future missions by promoting heritage, interface standardizations, while increase the overall computing power installed. Compared to a centralized architecture, decentralized architectures have an incremental design in nature, meaning that features can more easily be inherited and upgraded from mission to mission. Fundamentally, the use of distributed avionics implies more flexibility in terms of architecture comparing to the needs. It has already been demonstrated that a certain number of µ-RTUs and mini-RTUs could perform almost all the functions needed in the avionic. For some programs, new specifics needs are found and exposed to a centralized avionics with a single RTU and this shall be redesigned. Therefore, in a distributed avionics, this new micro/mini RTU generation would lead to avoid non-recurring costs because only a part of these micro or mini RTU would be modified.

- **High performance green propellant**: As indicated previously, LMP-103S possesses a higher density and a higher specific impulse (Isp) compared to hydrazine. Due to its lower toxicity, it is safer (and therefore cheaper) to handle than Hydrazine. This means a lower mass in space for future missions and safer working conditions for employees during the propellant loading operations, which could be done directly at the supplier site.

5. MATURITY OF THE CONCEPT

> *ESA has time to mitigate the programmatic risk for a future GreenSat by promoting the development of the solutions proposed and conducting appropriate de-risking activities.*

The solutions proposed are feasible in the mid-term timeframe provided sufficient development budget and effort can be allocated. Rather than targetting specific missions, these options have a broad scope of applications. This means that their development could be done independently of a particular mission, thus removing programmatic risks. Moreover, the development roadmaps proposed are consistent with exisiting development activities and technological trends observed in the space sector.

- **The development of lightweight ELO solar cells** is aligned with the ongoing effort to increase the power density of future solar array architectures (e.g. TAS patended flexible SA architecture). Specific challenges with the ELO technique will consist in optimizing the substrate removal and reclaim step to ensure a sufficiently high throughput. De-risking activities shall also be conducted on a small scale PVA to identify a suitable blanket material.

- **The development of a distributed architecture** is aligned with the NewSpace approach and foreseen increased use of COTS components in future satellites. Already employed in the automotive industry, the shift towards a decentralized avionics is enabled in the space sector by the progressive miniaturization of electronic components. Over the years, the automotive industry has faced a profound disruption with the new competitors from IT and electronics worlds. It is now a standard in the automotive industry that decentralized architecture is a solution for the present and the future of cars. In fact, the amount of sensors in cars grew exponentially and the processing power is now consequent. In the context of the space sector, it can be anticipated that the main difficulty will be to define a micro-Node architecture that is neither too generic to serve useful function neither to specialized that it prevents standardization. This means that a trade-off shall be conducted in ulterior project phases to arbitrate between generic micro-RTUs and more specialized mini-RTUs .

- **The adoption of Green propellant** is consistent with the ongoing effort to qualify 1N and 22N thrusters (which will fly on the PACE mission).

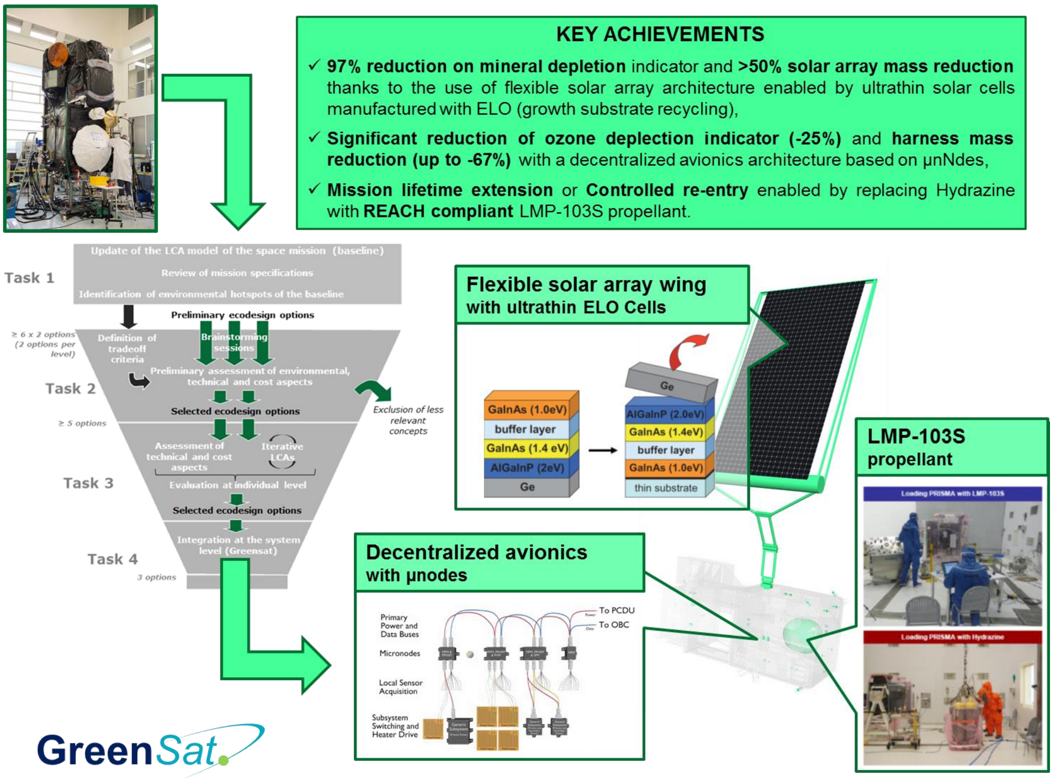
6. CONCLUSIONS AND WAY FORWARD

ESA can turn the threat of environmental challenges into innovation opportunities for the European space industry by promoting the development of the GreenSat Eco-Design solutions.

Following ESA's LCA guidelines and an Eco-Design approach, the concept identified by the consortium succeeds in simultaneously reducing the environmental footprint of a typical ESA mission while allowing meaningful improvements in term of cost and performance. With the proper development effort and resources, GreenSat will allow ESA to promote durable improvements of the European Space Industry, leading to:

- **Reduction of the environmental footprint** of future space missions on several indicators without increase on the others
- **Facilitate** the **compliance** of future space missions with respect to **SDM requirements**
- **Improvements** in the **performance and cost** of its missions

The preliminary comparison between development cost and recurring savings show that the ROI would be between 2 to 5 missions, depending on the option considered. A phase A study would allow to consolidate these estimations for the technologies eventually retained by ESA.



KEY ACHIEVEMENTS

- ✓ **97% reduction on mineral depletion** indicator and **>50% solar array mass reduction** thanks to the use of flexible solar array architecture enabled by ultrathin solar cells manufactured with ELO (growth substrate recycling),
- ✓ **Significant reduction of ozone deplection indicator (-25%)** and **harness mass reduction (up to -67%)** with a decentralized avionics architecture based on µnNdes,
- ✓ **Mission lifetime extension** or **Controlled re-entry** enabled by replacing Hydrazine with **REACH compliant** LMP-103S propellant.

Beyond the results of this case study of Sentinel 3, this activity was also a feasibility study of the implementation of eco-design in space missions. This project provided a good first step with insightful results but also first tools and methodological propositions for a broader dissemination of eco-design into the European Space Industry:

- **Development of an ad hoc methodology to identify, assess and discriminate eco-design concepts for one given mission.** Such an approach is reproducible for other space missions and shall be further developed by ESA and its stakeholders, in particular concerning the aggregating method of environmental impacts between the various indicators used in LCA.
- **Deed to complete ESA LCA Handbook with guidance for application in earlier design stages** of space missions. This work is to be initiated in the (on-going) activity on future standard EO platforms in which Thales Alenia Space is involved.
- **Suggestion to involve in the mid-term more people into eco-design procedures.** In other words, eco-design experts shall translate LCA results into technical/operational terms for system and design engineers. In a wider perspective, ESA could keep pursue its efforts towards a better appropriation of Life Cycle Thinking towards the whole industry, with the help of LSIs to pass on the knowledge to the whole European space value chain.

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