 

Space Circular Economy

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About the Authors

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The Circular Economy Narrative

What is a circular economy?

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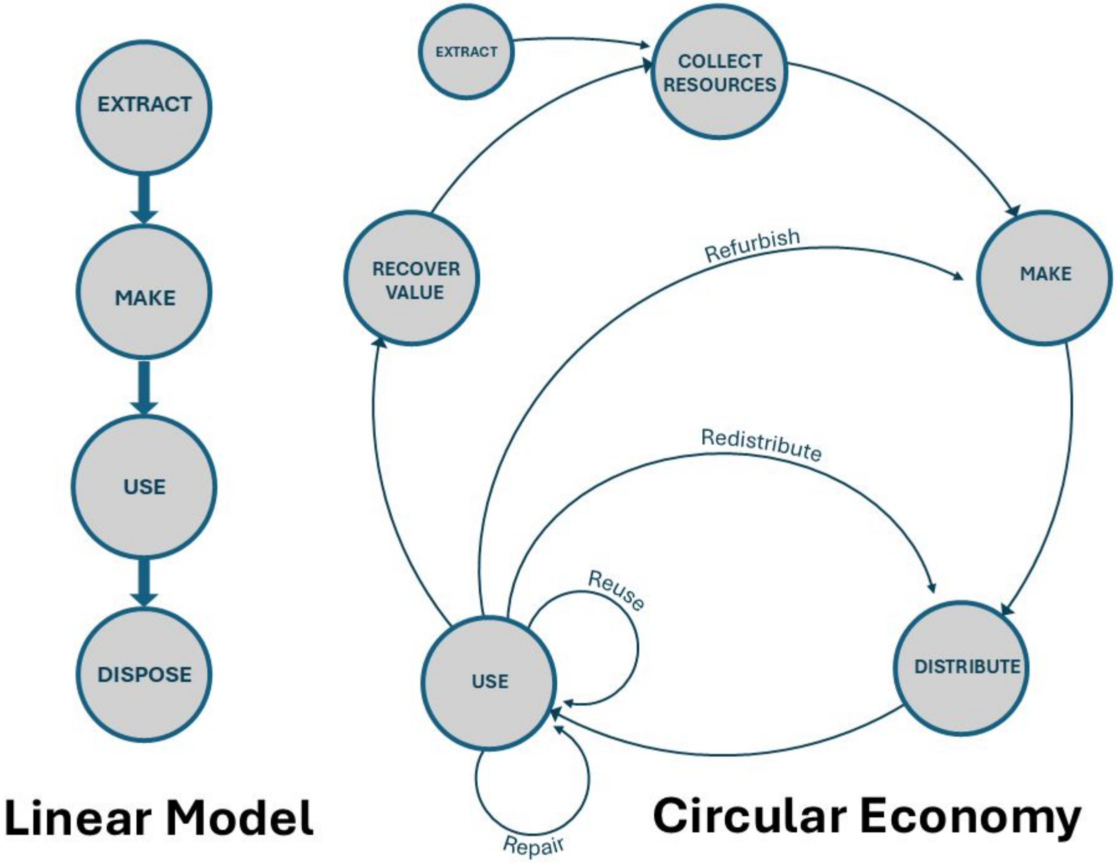
What is a Circular Economy?

- **Defining a CE is challenging**
  - 114 CE definitions **(Kirchherr, 2017)**
  - 221 CE definitions **(Kirchherr, 2023)**

- *“[An] economic system that uses a systemic approach to maintain a circular flow of resources by recovering, retaining or adding to their value while contributing to sustainable development”*

ISO 59004

- **A circular economy envisaged as a way to decouple economic activity from resource extraction**



A comparison of the dominant linear model of our industrial economy and a circular economy.

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What does a Circular Economy Look Like?

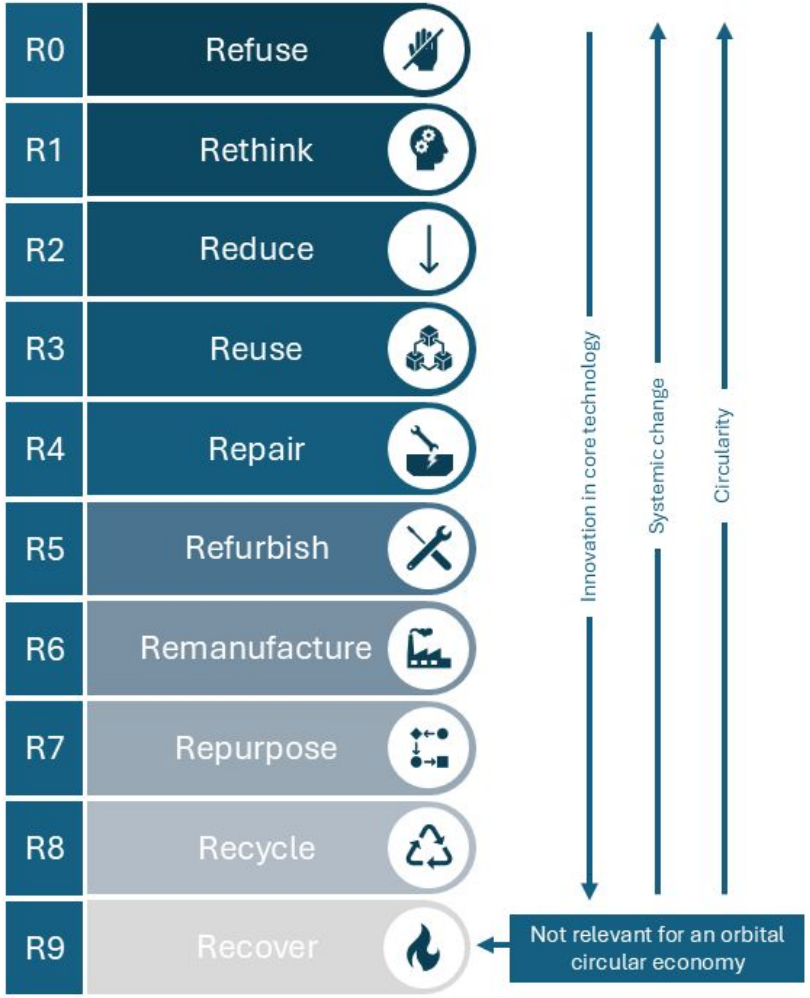
The Circular Economy is often decomposed into circularity strategies or “R’s”

- 3Rs (Reduce, Reuse, Recycle)
- 10Rs (See figure)

These strategies are hierarchical

- For example, it takes fewer resources to refuse to create a system than it does to refurbish one

A circular economy is one where **resources are largely retained** through these circularity strategies



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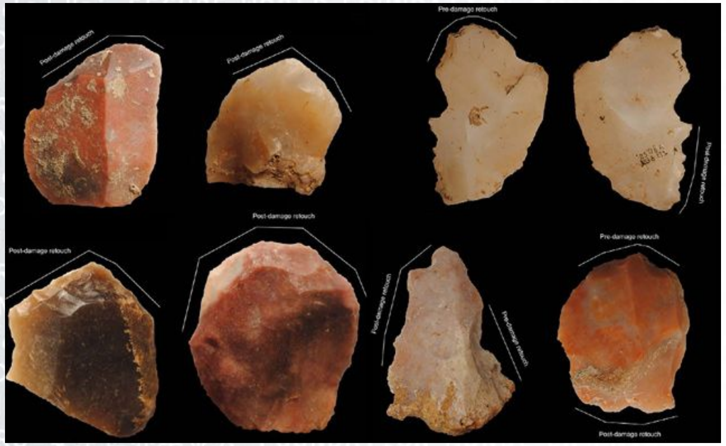
Historical Context

Circularity is not a new concept, and ‘Circularity strategies’ been employed in various historical settings where materials are scare

Old Stone Age
People **recycled stone tools** to save time, effort, and raw materials.



Four endscrapers retouched after fire damage, left, and four double tools retouched before and after fire damage

Credit: M. Vaquero et al.,2012

Ancient Rome
Laws and public systems encouraged **reuse (spolia)** and efficient water management.

Spolia in the city wall of İznik, Turkey, at Lefke Gate

Credit: Dosseman, via Wikimedia Commons.

Edo Japan:
Strong **reuse networks** and widespread literacy helped spread **repair/reuse** know-how and keep materials in circulation.

The ancient Japanese art of kintsugi involves the visible mending of broken pottery

Credit: (Credit: Getty Images)

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A Circular Economy in Space

Definitions and examples of circularity

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Our Definition of a Circular Economy in Space

Starting Definition (based on ISO 59000 and UN COPUOS LTS Guidelines)

“In a circular space economy, novel methods of design and managing space systems allows systems, subsystems, components, and materials to remain in orbit and be refurbished or re-used using an ecosystem of advanced in-orbit servicing techniques. This approach will preserve the space environment for future generations while meeting current economic needs.”

Revised Definition:

“A circular space economy is one in which space systems are designed and operated in a manner that enables those systems and their subsystems, components, and materials to remain in use through an ecosystem of space-based servicing and manufacturing techniques. This approach seeks to ***minimize waste, optimize resource use, and preserve the space environment*** *for future generations, while supporting the long-term sustainability of space activities in all its aspects.”*

Defining a Circular Economy in Space

What can we learn from other sectors?

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Marine Debris vs Space Debris

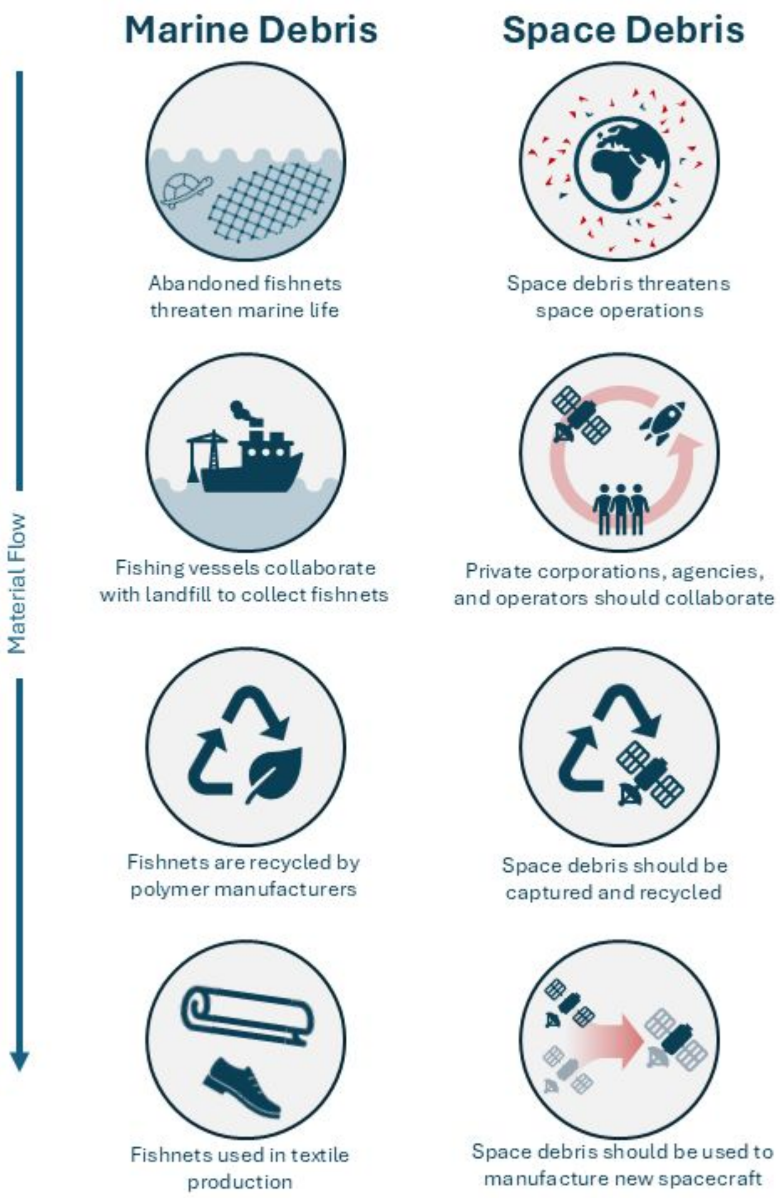
Napper et al. (2025) compared marine debris to orbital debris.

Similarities include:

- ❑ fragmentation patterns (physical abrasion, thermal, chemical/UV)
- ❑ cumulative debris trends from 1960s to today in orbit and in ocean
- ❑ ownership and management challenges (50% of the Earth’s surface are international waters)

Translatable space debris mitigation lessons:

- implement extended producer responsibility;
- develop and enforce international legislation with accountability (e.g., fines, incentives);
- incentivize innovation in debris mitigation; and
- foster science-based cooperation.



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Defining a Circular Economy in Space

What is the space sector already doing?

Circular Strategies in Space I

Refuse

Difficult to prevent duplication driven by commercial, military, and strategic interests.

Rethink

Servitization enables multi-mission satellites, lowering costs and helping limit debris growth.

Reduce

Space ecodesign targets Earth-based impacts, supported by ESA's LCA methods since 2009.

Intelligent Use of Resources in Space

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Circular Strategies in Space II

Reuse

SpaceX’s reusable Falcon 9/Heavy ,and planned fully reusable Starship, have cut launch costs, while in-orbit satellite reuse remains rare (e.g. AMC-14).

Repair

Repair in space is led by long-term ISS maintenance and emerging robotic life-extension missions, but demand for repairing unprepared legacy satellites remains limited.

Refurbish

5 Space Shuttle servicing missions refurbished the Hubble Space Telescope through optics correction and repeated upgrades over 16 years.

Longer Life Cycles in Space

Circular Strategies in Space III

Remanufacture

No in-orbit remanufacture has yet occurred.

Repurpose

Repurposing remains largely terrestrial, with only exploratory in-orbit concepts to date.

Recycle

While debris recycling is still theoretical, the ISS demonstrates viable recycling of plastics and consumables.

Longer Life Cycles in Space

Recycling

Enabling Technologies

Introduction to In-Space Servicing, Assembly, and Manufacturing

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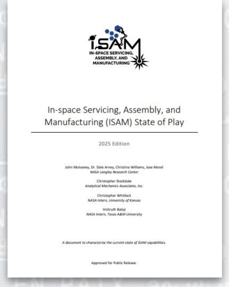
A Brief Introduction to ISAM

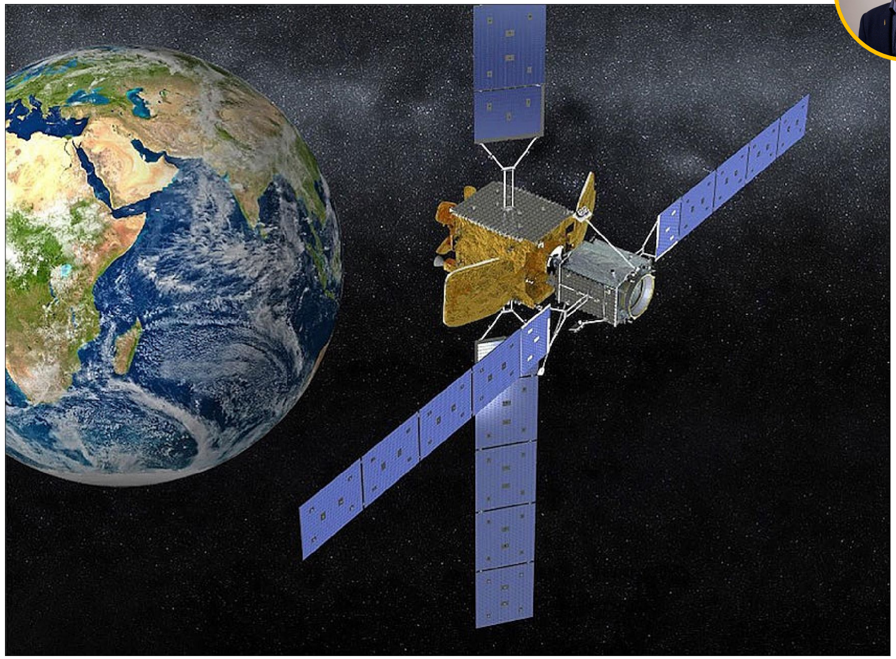
ISAM (In-Space Servicing, Assembly, and Manufacturing) refers to missions and technologies which enable inspection, repair, upgrade, assembly, relocation, and construction of space assets.

This includes:

- Refuelling satellites
- Extending satellite lifetimes (see MEV-1)
- Assembling space stations
- Servicing and refurbishing satellites



Recommended Reading on ISAM
2025 Edition of NASA's ISAM State of Play Report



MEV-1
Artist's rendition of the Intelsat 901 satellite (left) after the docking with the MEV-1 (right).

MEV-1 docked to Intelsat 901 in 2020 and extended the satellite's lifetime through AOCS takeover.
Image credit: Northrop Grumman Innovation Systems.

Key ISAM Technologies

01 — Advanced Robotics

- **Past examples:** ISS construction & Hubble servicing relied heavily on astronauts supported by robotics.
- **Key tech for robotic servicing:** target tracking (vision + pose/motion), reliable capture/docking, contact dynamics modelling, and coordinated multi-arm control.

02 — Verification and Validation Technologies

- **In-orbit V&V is challenging:** most verification/validation relies on ground facilities, and in-space assembled systems may not be fully tested end-to-end.
- **Autonomy raises the stakes:** V&V may need robots/EVAs, and non-deterministic behaviour can lead to unforeseen failures.

03 — Modular Spacecraft with Standard Interfaces

- **Modular spacecraft are a core ISAM enabler:** designs range from large functional modules (propulsion/payload/bus) to "satlets" assembled into a larger system.
- **Main challenge:** designing robust attitude and thermal control for modular architectures.

04 — In-Space Manufacturing Processes

- **In-space manufacturing/assembly tech is mostly ISS-driven:** additive manufacturing is the most mature; welding and forming are less developed.
- **On-orbit assembly concept example:** the (now-cancelled) OSAM-1 planned to assemble an antenna in orbit.

05 — Technologies for Rendezvous and Proximity Operations

- **ISAM needs safe close-proximity ops:** clients can add aids retroreflectors / transponders /fiducials) and chasers use sensors (LiDAR + visible/IR cameras), alongside robust procedures.
- **Standards improve safety & interoperability:** e.g., ESA's close-proximity guidelines and CONFERS/ISO principles for RPO.

Case Studies

Space Circularity in Practice

Refurbishing the Hubble Space Telescope

Hubble was designed with maintenance in mind.

Servicing missions were launched in 1993, 1997, 1999, 2002, and 2009 to install corrective optics, replace instruments, and replace defective components.

Key Takeaway

A serviceable design enabled both planned upgrades and fixes for unexpected issues (e.g., the flaw in Hubble's primary mirror).

Hubble Space Telescope
The preparation of Hubble for servicing made unplanned fixes substantially easier, and five successive servicing missions have kept Hubble at the forefront of space-based astronomy.

Image credit: Freepik/Doomu

Are Reusable Launchers Circular?

In 2024, SpaceX dominated the launch market, flying 52% of successful orbital launches[1].

This market dominance is largely because partially reusable launchers are cheaper (roughly $10,000 per kg instead of $2,600 per kg).

The fall in launch prices has led to a deluge of relatively cheap satellites in LEO, which are not designed for circularity.

Falcon 9 Laucnher
SpaceX's Falcon 9 rocket is partially reusable and stages are routinely reflown, reducing costs as well as reusing existing hardware.

Image credit: Wikimedia

[1] Our World in Data

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Creating a Circular Economy in Space

Benefits, Challenges, Risks

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Expert Interviews

Participant Cohort:

- 14 experts contributed
- Perspectives of participants from academia, industry and space agencies
- Expertise in policy, space law, physics,orbit recycling, space surveillance and supply chain
- ESA, OHB, Durham University, ESRIC, BryceTech, Leiden University, ClearSpace, and other organisations.

Benefits of a circular approach to space activities

Benefit	Mechanism	Impact
Environmental Benefits	*Reduce Launch Numbers*	*Less Emissions (carbon dioxide, chlorine oxide and nitrogen oxide) *Reduces dependency on Earth based materials *Less congestion
Economic Benefits	*In-orbit manufacturing*	*Lower logistics costs *New business models creation *Additional revenue stream from the recycled/manufactured material
Operational Benefits	*Servicing and Standardisation*	*enhance operational flexibility due to like less space debris *less manoeuvres, less operational costs *flexibility to refurbish and repair with standardisation

Outlook and Trends (10-15 Years)

What are the highest-value circular interventions you expect to see in space?

- **In-orbit servicing for life-extension** (refuelling, repair, modular replacement);
- **Design & standards** for serviceability
- **Governance & market enablers** (risk-based regulation, U.S.–-EU alignment and interoperability, commercial contracts).

“Satellite life extension is one of the prime ones... we will see the satellites being refuelled or repaired in space... designed for repair and servicing.”
- A UK Professor

“A key enabler in the next 10–15 years is US–EU alignment... simplification and standardisation so systems are compatible... not just demos but commercial contracts that enable servicing and reuse.”
- A Swiss strategy manager (space policy & governance)

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“We’ll probably never make it perfect—people aren’t perfect—but it doesn’t need to be. We just need a good-enough version that’s better than today[‘s].”

-Space Sector CEO

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Conclusions

Takeaways and Unanswered Questions

Is there a case for a circular economy in space?

The Argument for a CE

- Sustained use of outer space for use of future generations
- Improved efficiency of spacecraft
- Unlocking new business models
- Environmental benefits

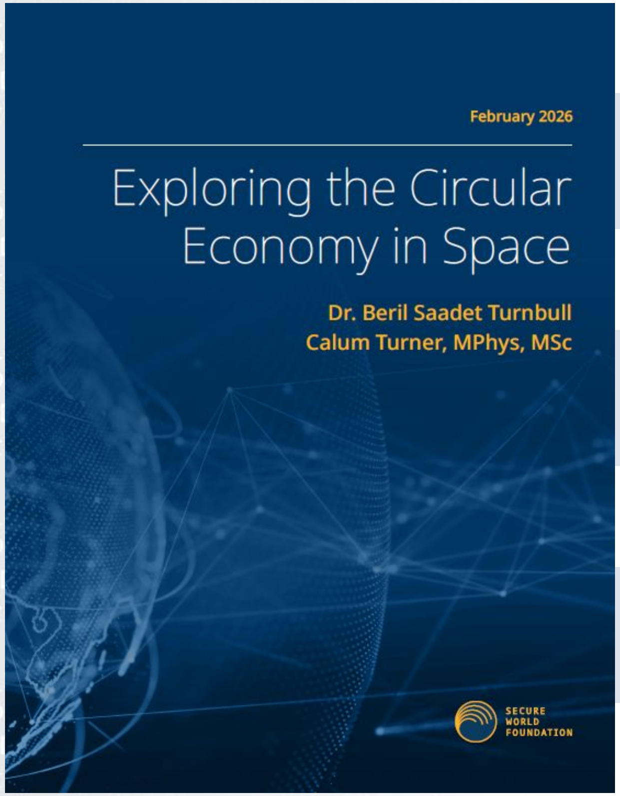
The Argument against a CE

- High costs, uncertain business cases, and risk averse culture
- Challenges of orbital environment
- Falling launch prices
- Lack of coordination and competition between space actors

On balance, we are cautiously optimistic. Circularity is achievable in space in stages if policy, markets, and technology coevolve.

Interested in Learning More?

The full report contains more detailed information, more case studies, and a collection of key takeaways distilling the outcomes of our research.



- **15** Key Takeaways
- **3** Case Studies
- **14** Expert Interviews

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2025 Space Sustainability Research Fellows

Exploring the Circular Economy in Space

by Beril Saadet Turnbull
and Calum Turner

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swfound.org/SSRI-25-circular-economy

Thank You

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