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Space and the Circular Economy: Exploring Expert Perceptions

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Space is facing significant sustainability issues such as space debris generation, light pollution, green-house gas emissions, and ozone layer depletion due to congestion of orbits, increase in rocket launches, and future mega constellations. Without including sustainability in the mission development framework, present and future space activities such as satellite internet networks, space resource utilization, solar power satellites, and space-based climate action could be compromised. To date, space endeavours mostly rely on linear economy principles, following the "make, take, waste"-approach, and literature on how to transition to a circular space economy (CSE) remains limited. However, the implementation of circular economy (CE) principles in space activities requires a radical shift in the way mission concepts and space architectures are developed. A CSE may be crucial to ensuring the sustainable use of space and its resources, while an optimized use of existing and future space assets promises lower long-term costs, in addition to safeguarding sustainability on Earth and in space. The objective of this work is to gather, process, and synthesize qualitative and quantitative data on barriers, enablers, uncertainties, and challenges towards reaching the full circularity potential of the space ecosystem. To this aim, a diverse pool of experts in CE, CSE, and space engineering from universities and research institutes, private sector, and space agencies was included in semi-structured interviews. The result is a first of its kind empirical dataset, which not only provides the ground for further, thorough research, but contributes to the discussion around space sustainability- and CSE-definition, lessons learned from terrestrial CE application, and effects on the space ecosystem. While the expert perceptions diverge on the future grade of circularity implementation, they also express concerns about regulatory aspects–but remain confident in the long term. Broadly speaking, the views differ depending on the organizational and individual backgrounds of the experts, while they align on CSE's outstanding potential.

Keywords: Circular space economy, expert perceptions, circular economy, space sustainability, space systems engineering, circular design, large space structures, climate change

1. Introduction

The rapid growth of space activities has created a need to implement sustainability in our space operations [1]. To tackle the issue, the capability to clean orbits of space debris has advanced to the point where it will become a reality in the coming years. However, the expected drop in launch costs [2] and increasing frequency of rocket launches [3, 4] and subsequently reentries will further contribute to the congestion of orbits, debris generation, light pollution, greenhouse gas emissions, and ozone layer damage, among other issues. This raises the need for a more comprehensive solution. Drawing from terrestrial applications, sustainability can be integrated through circular economy (CE) principles [5–10].

When applied to space, this concept offers a promising approach to ensuring the sustainability of outer space activities, as envisioned by the United Nations Office for Outer Space Affairs (UNOOSA) [11]. In that context of a sustainable and responsible use of space, it could enhance the long-term viability of key initiatives such as mega-constellations, space resource utilization, large space structures like solar power satellites (SPS) [12], and space-based climate action, particularly sunshades [13–15].

The CE concept evolved in the late 1970s in response to growing environmental concerns [5]. Over the last 10

List of acronyms and abbreviations

9R	Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover
AOCS	Attitude and Orbit Control System
CE	Circular Economy
CEO	Chief Executive Officer
CONFERS	Consortium for Execution of Rendezvous and Servicing Operations
COPUOS	Committee on the Peaceful Uses of Outer Space
CSE	Circular Space Economy
DLR	Deutsches Zentrum für Luft- und Raumfahrt (en: German Aerospace Center)
EoL	End of Life
ESA	European Space Agency
GEO	Geosynchronous Orbit
GNC	Guidance, Navigation, and Control
ISO	International Organization for Standardization
ISS	International Space Station
ITU	International Telecommunication Union
L	Sun-Earth Lagrange Point
LCA	Life Cycle Assessment
LEO	Low Earth orbit
MEV	Mission Extension Vehicle
MS	Microsoft
NASA	National Aeronautics and Space Administration
OSAM	On-Orbit Servicing, Assembly, and Manufacturing
OSIRIS-APEX	Origins, Spectral Interpretation, Resource Identification, and Security – Apophis Explorer
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, and Security – Regolith Explorer
SET	Polyethylene Terephthalate
SPS	Solar Power Satellites
UN	United Nations
UNOOSA	United Nations Office for Outer Space Affairs

to 15 years, CE has gained momentum as industries and society on Earth contend with the challenges of resource depletion and waste management [9, 16]. The core idea of CE is to minimize waste and extend the life cycle of products through various strategies. To group and visualize these strategies, the 9R framework (see Fig. 1) has been introduced. It provides a comprehensive and widely recognized categorization [7]. Other frameworks, such as the 3R [17], 10R [8], and the "Butterfly Diagram" of the Ellen MacArthur Foundation [5] vary in complexity, with even larger frameworks conceivable. However, the 9R framework strikes an effective balance between simplicity and depth, focusing on key strategies such as rethink, reuse, refurbish, and recycle without overcomplicating the analysis.

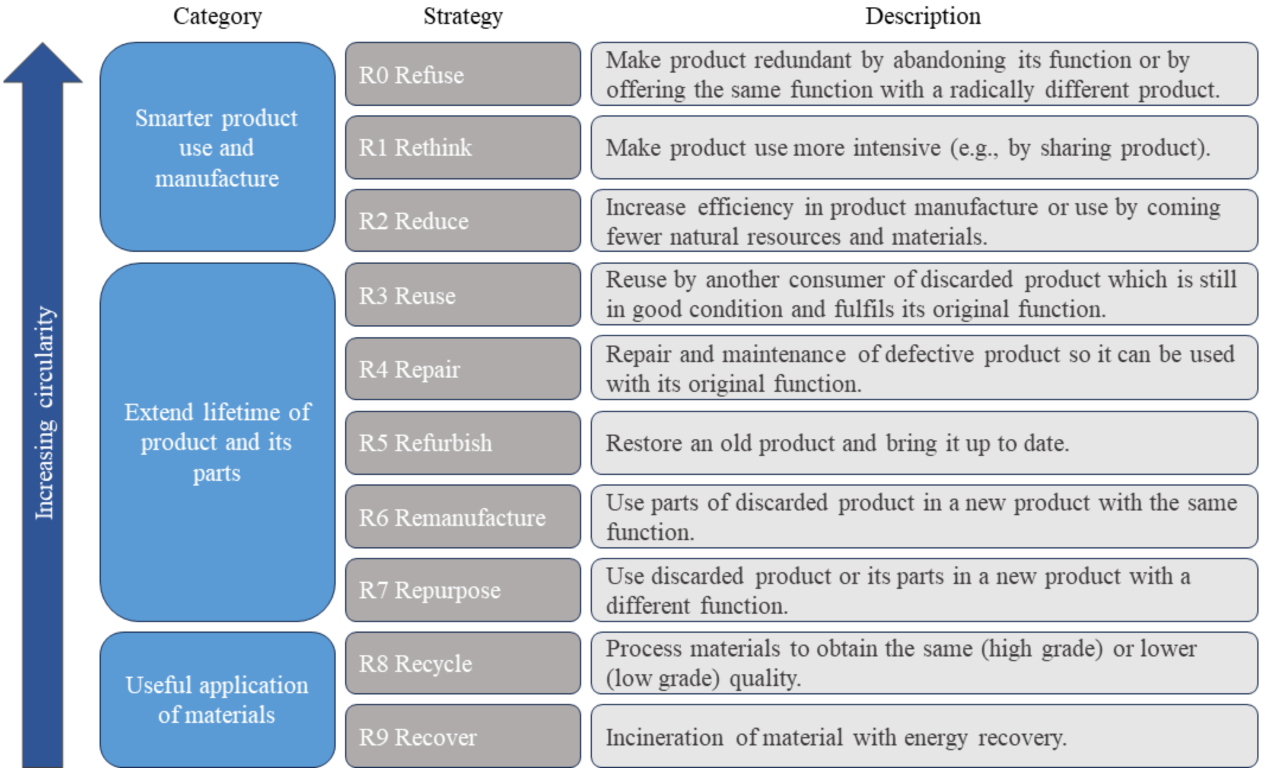
The application of CE principles to space activities has enormous potential to address current and future challenges. A circular space economy (CSE) could reduce waste, extend the lifespan of spacecraft, and lower long-term costs by reusing resources and designing systems that are modular, serviceable, and recyclable. For example, in-orbit servicing—where satellites are refueled, repaired, or upgraded while in space—could drastically reduce the need for launching new satellites, helping mitigate the space debris problem. Additionally, repurposing and recycling materials in space could reduce dependency on Earth for resupply missions, especially in long-term projects like Moon or Mars exploration.

However, the concept of CE is still evolving. A recent study identified over 221 definitions of CE [10], reflecting the complexity and variability of the concept. It took 50 years to introduce an International Organization for Standardization (ISO) standard for the CE on Earth, which was released in 2024 [18]. It is reasonable to argue that a similarly uncertain path lies ahead for defining a CSE. While some space missions have demonstrated the feasibility of a CSE to some extent, examples will be given in Section 3, the space sector is only beginning to explore how circular principles can be fully integrated into space missions. Although the need for a CSE is becoming more evident, there is no universal agreement on what it should include or how it should be implemented.

Organizations like the European Space Agency (ESA), through initiatives such as the Clean Space program and the 2023 White Paper on enabling a CE in space by 2050 [19], are promoting sustainable practices while outlining key challenges and actions to implement circular principles in space activities.

Given that publications on the topic are still limited, this interview study takes place at an opportune time. To the best knowledge of the authors, only one interview study has explored reuse in a CSE context [20], highlighting the need for further, thorough investigation. By conducting a series of interviews with professionals in CE and space engineering, this research aims to synthesize knowledge from both domains to explore the feasibility and challenges of implementing a CSE. The goal is to address gaps in the current literature and contribute to the ongoing conversation about space sustainability and the definition of a CSE. Additionally, this study will examine how CSE could enable the development of mega-structures in space. By investigating how CE principles can be applied to space activities, this research also seeks to understand the enablers, barriers, and uncertainties that influence the transition to a CSE. It provides a foundation for future research by highlighting best practices, lessons from terrestrial CE applications, and the key challenges that must be overcome to make the CSE a reality.

The paper is structured as follows. First, Section 2 outlines the research design. Following this, Section 3 presents the results of the present study, and synthesizes the study's findings. Section 4 draws conclusions and outlines future work for this ongoing study.



Category	Strategy	Description
Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product.
	R1 Rethink	Make product use more intensive (e.g., by sharing product).
	R2 Reduce	Increase efficiency in product manufacture or use by coming fewer natural resources and materials.
Extend lifetime of product and its parts	R3 Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function.
	R4 Repair	Repair and maintenance of defective product so it can be used with its original function.
	R5 Refurbish	Restore an old product and bring it up to date.
	R6 Remanufacture	Use parts of discarded product in a new product with the same function.
	R7 Repurpose	Use discarded product or its parts in a new product with a different function.
Useful application of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality.
	R9 Recover	Incineration of material with energy recovery.

Fig. 1. The 9R framework of a CE, adapted from Kirchherr et al. [7].

2. Research methodology

This study employs a qualitative research approach to gather insights from professionals in the space industry and the CE domain. The experts' professional backgrounds are documented in Table 1, while their characteristics and professional work experiences are presented in Table 2. The limited understanding of the CSE, including its definition and the unclear path toward its realization, despite the evident sustainability issues in the space industry, motivates this study. The methodology includes semi-structured interviews and thematic analysis to develop a comprehensive understanding of the challenges, opportunities, and potential strategies for integrating CE principles into space missions: "... interviews of this kind enable us to engage with unique sources of novel data, and to explore how the complicated, emerging developments in this domain intersect with and promote experts' perceptions, beliefs, and values" [22]. The research methodology is visualized in Fig. 2. Anonymizing the results gives participants the freedom to express their views openly. The open approach to presenting the results allows expert perceptions to guide and shape the discussion, which is considered appropriate given the novelty of the research field. [22]

The primary data collection method involved conducting semi-structured interviews with professionals from academia and research institutes, the private sector, and space agencies. Participants were chosen based on their experience and expertise in space systems design and engineering, space sustainability, CE practices, as well as their contributions to peer-reviewed publications. The interviews lasted approximately 60 to 90 minutes and were conducted with open-ended questions following an interview guideline. This approach allowed for a deep exploration, subsequent comparison, and analysis of the participants' personal experiences and answers to a defined set of questions. Additionally, it provided the flexibility for follow-up discussions on unforeseen topics, which is a specific goal of this study. The interviews focused on four core areas: (i) lessons learned and insights gained from the participants' individual professional careers, (ii) definition of a CSE, (iii) exploring the application of CE principles in space missions while identifying enablers, barriers, and risks to achieving circularity in space, and (iv) impact of a CSE on the space ecosystem. The interview data was collected via video conferencing using Microsoft (MS) Teams, and the interviews were recorded and transcribed for analysis. In advance, participants were asked

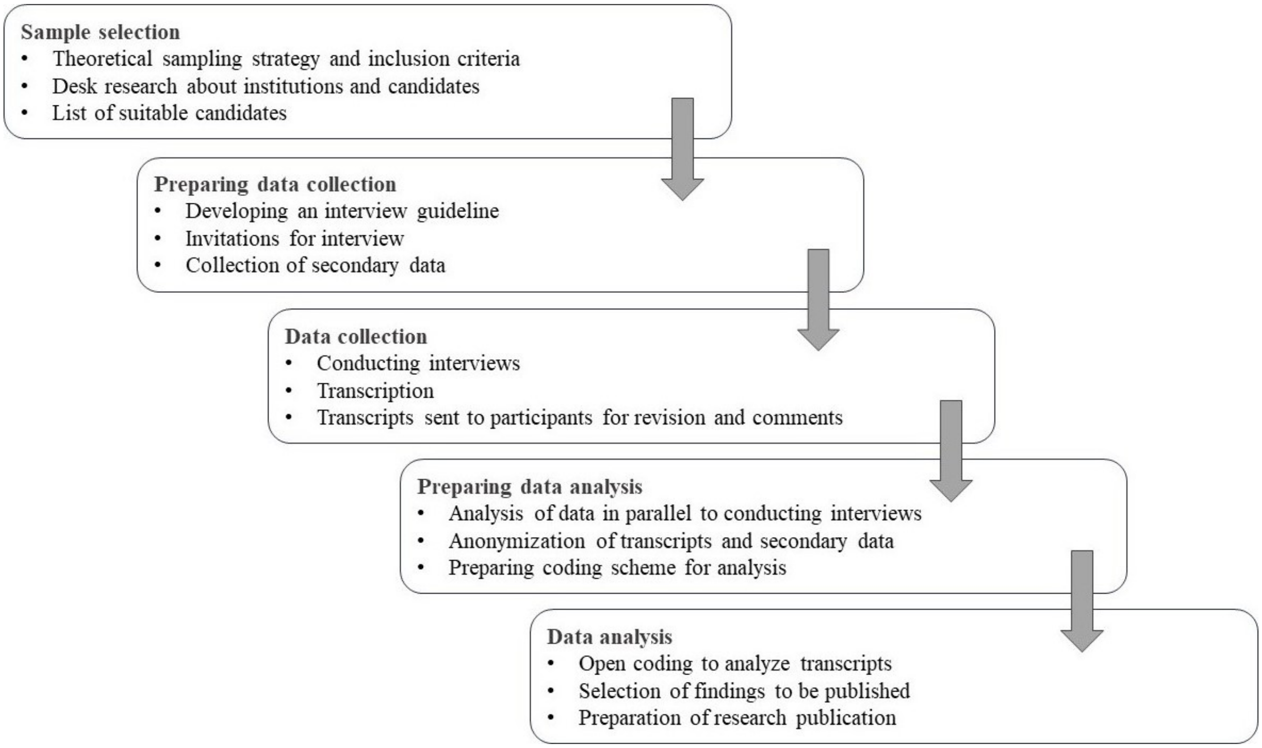


Fig. 2. Methodological flowchart, adapted from von Kolpinski et al. [21].

to fill out their professional background information (secondary data) in MS Forms to facilitate the interview process, and they gave informed consent for their participation and the use of their responses.

Overall, 10 interviews were conducted in July and August 2024. Each participant was given a short introduction to the research project and topic. The interview consisted of 8 open-ended questions, with different potential follow-up questions prepared for each, based on the participant's background and expertise. For example, questions included: "What is your current understanding of the CSE?", "How would you implement circularity in space systems?", and "What effects might a CSE have on the space ecosystem?" After finishing each interview, a transcript was created based on the video recording. To anonymize the data, the transcripts were cleared of personal information that could identify the participants, and each participant was assigned an individual respondent number (e.g., R01 for respondent 1). Transcripts were then sent out for approval by the participants. After receiving the approved transcript—and, in some cases, after correspondence and slight modifications—the video recordings were permanently deleted. In the subsequent analysis of the transcripts, answers were assigned to the questions asked using an open coding approach. New codes were created when unexpected topics arose (e.g., "CSE examples in history"). The interview guideline was logically structured with the final presentation in mind, allowing the structure of the interviews to align with how the results are presented in this publication.

The present approach does have its shortcomings. Some lie in the semi-structured interview method itself. It is unlikely that results can be replicated exactly in the same way, as perceptions of some experts may have changed over time. Even though the questions were thoroughly prepared and peer-reviewed to avoid introducing any bias in the answers, they may have still led participants to give responses they might not have otherwise provided. The relatively small sample size of interview participants may also limit the generalizability of the findings to the broader space industry. Additionally, the focus on experts from the European space sector provides a limited global perspective on CSE. However, the authors are aware of these limitations, and the presented results are considered preliminary, as this study is still ongoing and these issues will be addressed in future work.

3. Results and discussion

We have organized the experts' responses into analytical themes, which emerged both organically during the

Table 1. Overview of the anonymized participants' background. The columns have been arranged in alphabetical order each. There is no correlation between institution, job title, and main research area / job focus. This approach preserves anonymity while maximizing the amount of information shared about the participants.

Institution	Job Title	Main Research Area / Job focus
Anonymous Circular Economy Startup	Associate Professor	Asteroid Lander, CE, GNC, Industrial EoL Processes, In-Orbit Servicing, LCA, Mission Design for GEO In-Orbit Servicing Satellite, Product Design, Sample Return Missions, Satellite Communication, Satellite Technology, Small Spacecraft, Solar Sails, Space Debris Mitigation, Space Exploration, Space History, Space Policy, Space Resources, Space Sustainability, Space Systems, Space Systems Engineering, Sustainable Design, Sustainable Development, Systems Engineering, Systems Engineering for In-Orbit Servicing
Anonymous In-Orbit Servicing Company	CEO of Startup	
DLR German Aerospace Center	Professor	
European Space Agency	Research Associate	
European Space Agency	Research Scientist	
Korea Aerospace University	Senior Project Manager	
Luxembourg Institute of Science and Technology	Systems Engineer	
Luxembourg Space Agency	Systems Engineer	
University of Luxembourg	Systems Engineer	
University of Luxembourg	Systems Engineer	

Source: Experts; CEO = Chief Executive Officer; DLR = Deutsches Zentrum für Luft- und Raumfahrt (en: German Aerospace Center); GEO = Geosynchronous Orbit; GNC = Guidance, Navigation, and Control; EoL = End of Life; LCA = Life Cycle Assessment.

Table 2. Summary of expert characteristics and professional experiences.

Category	Value
Total Number of:	
Experts	10
Institutions	8
Countries	4
Level of Education:	
Professorship	2
Doctorate / PhD	3
University Degree / Equivalent	5
Cumultative Work Experience:	
Overall	123 y
Space Sector	67 y
Terrestrial CE	24 y
CSE	23.5 y
Average work Experience:	
Overall	12.3 y

Source: Experts.

interviews and through the interview structure. This section provides a brief glimpse into the wide range of themes covered and the depth of exploration in the full analysis: Section 3.1 presents perspectives on space sustainability, Section 3.2 offers insights into the scope of the CSE as envisioned by participants, Section 3.3 examines a selection of historical examples where CSE principles have been applied, Section 3.4 identifies enablers and challenges for achieving a sustainable CSE, and finally, Section 3.5 explores the role of the CSE as a critical enabler for large space structures.

3.1 Perspectives on space sustainability

Throughout the interviews, the experts offered a variety of perspectives on the concept of space sustainability. Clarifying this concept is essential to defining the scope of this study, as the implementation of a CSE is ultimately aimed at achieving long-term space sustainability [23].

R10 emphasized that sustainability, overall, involves ensuring the future availability of resources:

> Sustainability is a big word. I would say, in general, sustainability means that certain resources can be used by future generations indefinitely, in principle. This means that the use of those resources needs to be limited to some extent, though that's probably a consequence. Essentially, sustainability is about ensuring that resources remain available for future generations. Resources here can be broadly defined.

Focusing on the near-Earth space environment, R10 further elaborated:

> If we take this definition of sustainability or sustainable use of resources and apply it to space, the question becomes: "What resources exist in space?" First of all, there's space itself–orbital locations, for example. How can we ensure that certain orbital locations, like low Earth orbit, geostationary orbit, or other orbits, are available to future generations? That leads to questions about space debris, space debris removal, and so on.

R10 then expanded the scope of space sustainability to include deep space and celestial bodies:

> But if we look beyond space around Earth, we could consider the Moon or other celestial bodies. In that case, sustainability might mean re-

> stricting mining operations on the Moon to specific regions or perhaps certain layers of the lunar surface. We should also consider limiting pollution from mining operations, such as generating lunar dust, which, in some cases, could reach orbital speeds depending on the mining methods used. So yes, operations on celestial bodies are certainly an important aspect of sustainability in space.

Further in the discussion, R10 addressed the space sustainability paradox [24]. This paradox raises thought-provoking trade-offs between achieving sustainability in space and on Earth:

> ... but there's a third area that's a bit counterintuitive–how space can contribute to sustainability on Earth. This brings us to the trade-off between space and Earth. Could we do certain things in space to avoid sustainability issues on Earth? For example, is mining in space more environmentally sustainable than mining on Earth? There's also been recent discussion about power production in space–could that be more sustainable than producing power on Earth? These trade-off questions between sustainability on Earth and in space are very interesting. So, that would be my take on space sustainability in a broad sense.

While R07 and R10 share a similar vision of sustainability in general, R07 refers to established guidelines in the context of space sustainability and emphasizes the importance of moving toward a circular model as a means of achieving long-term sustainability:

> In the context of the space sector, space sustainability is defined by the UN [United Nations] Office for Outer Space Affairs, which provides these long-term sustainability guidelines. It defines it as the ability to operate continuously and maintain the space environment for present and future generations. I would add that this definition implies a certain static nature to sustainability, where I believe it's more about adapting processes and approaches so that we move from the current unsustainable practice of build it, fly it, use it, crash it, to a more circular model where we use the space environment in a way that maintains its balance, rather than polluting it endlessly.

For R06, space sustainability extends beyond environmental concerns to include economic efficiency:

> Well, I would say [space sustainability is about] maximizing the effect of the space mission for the resources you invest, specifically, maximizing the lifetime of the satellite for the given budget.

R06 further elaborates on the need to consider all involved resources, specifically emphasizing the importance of sustainability not only in the physical domain but also in the digital domain:

> When we talk about sustainability we want to use our resources efficiently, right? The frequency spectrum is a very limited resource that must be shared among all stakeholders, satellite operators, and so on. There are guidelines from the ITU [International Telecommunication Union] for frequency issues, and for space debris, we adhere to the Code of Conduct for Space Debris Mitigation.

In the context of economic considerations and space sustainability, R05 emphasizes the importance of efficiency in space missions. Like R07, R05 views a circular model as a potential solution for achieving long-term sustainability in space:

> So, sustainability for me is the optimization of resource use. In this case, we're talking about orbital resources, as well as space assets like spacecraft and managed objects in space. We need to optimize their use and possibly extend their lifetime to ensure long-term utilization. This is a bit of my concept; perhaps I should rephrase it differently, but the principle for me is this: try to achieve in the long-term that we can still use space in an optimal way, so future generations can continue to benefit from orbital resources and assets, and we can guarantee the services we have today in an even better way. I believe it's a really good timing to push for space sustainability and to push for a circular economy, especially considering the increase in the number of launches we've seen in the last few years.

These insights reflect a broad understanding of space sustainability as the responsible management of space resources, minimizing debris, and extending the operational lifespan of assets to ensure space remains usable for future generations. This holistic approach integrates both social and environmental responsibility, and economic efficiency to achieve long-term sustainability in space.

3.2 Scope of the CSE

Experts offered a wide range of perspectives on what should constitute the CSE. While it broadly refers to incorporating CE strategies (see Figure 1) into space activities–a lively discussion on the scope and definition of this concept is essential if we are to achieve it.

R09 shared the following initial thoughts on the CSE:

> So, the term circular economy makes me think of this "circle"–that's the point, right? You're supposed to have this loop where nothing ever stops and becomes waste. Nothing is wasted, everything is reused, with minimal impact on the environment.

R02 explained the concept of a CSE by moving away from the traditional linear process of conducting space missions:

> My understanding is that this concept involves applying circularity principles to space, which contrast with linear principles. Linear principles involve producing a product that eventually becomes waste, which can be categorized in various ways, such as environmental or economic. In contrast, circularity aims for 100% of a product to be reintegrated into the development process. For space, this means that anything contributing to the development of a space system, product, or service should not go to waste. Instead, it should be reused or repurposed, ensuring that nothing is lost, and everything is reintegrated into the development process. For example, this might involve repurposing or reusing a spacecraft in orbit rather than allowing it to become space debris.

R02 further envisions the CSE as a comprehensive ecosystem that integrates both space and terrestrial operations, involving every asset related to space missions:

> This applies to anything that contributes to space, including space systems, products, and services. This encompasses the ground segment, the space segment, suppliers, and even software that is not a physical product. Logistics are also included. Essentially, it should apply to everything that contributes to the space sector.

Similar to R02, R01 emphasized the role of a CE in specifically addressing the issue of space debris and highlighted the options to close the loop for space systems either in space or back on Earth:

> I would imagine it ... as having no waste in space. ... I mean, 100% of the economy in space would be circular. So that all resources we put in orbit or out of our atmosphere will somehow, after the intended use, will find another purpose. We can call that repurposing or it will be recycled. ... I think I read the statistics a couple of months ago, it was published by the European Space Agency. And in terms of the tonnage and the number of space debris objects that are already existing in space, it is just outstanding. So to me, a circular economy in space will basically mitigate that to make sure that everything is reused, recycled, repurposed out there in space or could come back to Earth and going to the conventional recycling facilities and such.

R07 envisions the CSE as a system that focuses on extending the life of platforms and reducing the need for rocket launches from Earth:

> For me, the circular economy in space involves having the technologies, infrastructures, operational practices, and regulations in place to use, reuse, and repurpose space assets. Instead of launching particular satellites for specific missions, we could have assets in space that last longer. This way, we can change payloads on persistent platforms and transfer components from one satellite to another, reusing as much material as possible that's already in space. Instead of launching entirely new systems, we aim to keep as much material as possible in space and reuse or update it as necessary.

In response to intensifying space operations, R05 stressed the need to optimize space resource usage, highlighting the role of the CSE in addressing these challenges. The expert sees the CSE as primarily focused on the space segment:

> With the new market trend for mega-constellations and more space activities, we need to think about optimizing the use of these resources, now that we have more and more objects in space, of course. And then I would say, considering what we're doing with space–specifically the space circular economy through in-orbit servicing and operations, ... in-orbit refurbishment, manufacturing, and recycling–I would say it's also a good time, especially with what is happening worldwide.

R10 takes a forward-looking approach, suggesting that the CSE could evolve by applying Earth-based principles in new and innovative ways:

> My take on the circular space economy would be to explore how we can use the principles of the circular economy, as developed on Earth, and creatively apply them to space. Maybe we could find new, surprising ways to implement a circular economy in space.

The experts provided varied yet aligned perspectives on the concept of a CSE, all emphasizing the necessity of integrating CE strategies into space operations. Some stressed the need for a comprehensive approach that includes both space and terrestrial infrastructures, while others see the CSE as only applying to the space segment. Additionally, experts suggested that the application of terrestrial CE models could lead to innovative practices in space. Collectively, these views underscore the critical role of a well-defined CSE in ensuring the long-term sustainability of space activities.

3.3 CSE examples in history

Several participants referenced real-world examples of circular strategies in space activities, highlighting past missions and technologies that embody CE principles. This demonstrates that, driven by an economic need, such strategies are feasible with both current and past technology standards.

R04 mentioned space stations as an example where circular strategies have been applied ever since:

> ... if you look at the space station, you already have this reuse of modules. As long as the outer stays intact, you can refurbish it on the inside completely. And that's been done with space stations since the very first one. So, we are, in a way, already there. There just needs to be a higher degree of awareness, and I think it's coming from the commercial space sector already.

More into detail, R03 cited the water recycling system aboard the International Space Station (ISS) as a prime example of CSE, specifically highlighting a biological loop:

> And that's exactly because you had to do it from the beginning [aboard the ISS]. There was simply no other option. So you had to reuse the water, even without thinking about circular economy. It was just a matter of necessity–there was no water, so you had to make sure you could reuse what you had.

Furthermore, the ISS serves as an example of the "rethink" strategy, where infrastructure is shared to achieve a more intensive use of resources in space. As R08 notes, another good example of this strategy is payload hosting, and we may see more of these activities in the future:

> I think it's all about having a controlled environment and sharing it among many different users. In the future, once you're able to control the debris, you might see a growing number of users and operators in space. At some point, you may need to share infrastructure. You can already see this happening in LEO [Low Earth Orbit], where single satellites host multiple payloads from various users and operators. The ISS is another example. So, I think sharing infrastructure becomes a key element in the future for larger infrastructure. With that, you also have this sharing of infrastructure in various ways, including satellite systems.

R05 discussed the significance of the Mission Extension Vehicles (MEVs), which extended the life of satellites in geosynchronous orbit (GEO):

> To give you an example, with AOCS [Attitude and Orbit Control System] takeover services, there were missions done by Northrop Grumman in the past, now Space Logistics, and their Mission Extension Vehicles. In this case, the client of this service was Intelsat, a space operator that was willing to pay for this type of service.

R05 further elaborates:

> [It] was really a breakthrough in terms of servicing ... what happened about five years ago, in 2019, with the launch of MEV-1 ... They were able to provide a service to a GEO satellite; in this case, we're especially talking about attitude control services. They captured a satellite in GEO and managed to provide AOCS takeover. The follow-up was MEV-2, and at the moment, we know there are other works from Space Logistics now, which is providing these Mission Extension Vehicle missions. Additionally, there are other agencies like NASA [National Aeronautics and Space Administration], which had the project OSAM, On-Orbit Servicing, Assembly, and Manufacturing. There's still ongoing work in terms of technology developments.

R04 referenced the OSIRIS REx (Origins, Spectral Interpretation, Resource Identification, and Security – Regolith Explorer) mission that was, after its completion in late 2023, turned into OSIRIS – APEX (Apophis Explorer) as an example of circularity by reusing a spacecraft for a new mission:

> I think it gets circular as soon as you use something for a purpose other than what it was originally intended for. This might already include extended missions, like, for example, the OSIRIS-REx mission. It delivered its capsule from Bennu to Earth, did a flyby, and is now heading to the asteroid Apophis. So that's already creating a circle. Once you don't build a new spacecraft but use one you already have, if it's more or less fully functional, you already avoid the end-of-life through repurposing. There will always be some downcycling, and eventually, there will be waste and feedstock that you'll need to replace. If you reuse it even once, you're already doing space and sustainability a great favor. Planetary science missions are really leading the way in this. It's very rare in low Earth orbit to reuse spacecrafts in this way, other than continuing their original mission. But if you use a spacecraft for another mission, saving the cost of building and launching a new one, you're already part of the circular space economy.

Focusing on the economic perspective of the mission, R04 adds:

> ... in extended missions like OSIRIS-REx going from Bennu to Apohpis, there certainly has been a trade-off metric that considers the cost of extending the mission by 10 years versus launching a new one or doing something completely different with the money from that existing science budget.

R07 pointed to the Hubble Space Telescope as an example of modular design, allowing for upgrades over its lifetime:

> ... looking at Hubble, where, weirdly, it's these nineties, early 2000s space infrastructures that are more circular than things we're building now. So the swappable payloads on Hubble are a good example; this instrument is still providing world-class science now because it has been upgraded over the course of its lifetime.

These examples illustrate how principles of the CE have already been applied in space, showing how resource efficiency, modularity, and life-extension can significantly reduce waste and optimize the use of existing space infrastructure.

3.4 Enablers and challenges for a sustainable CSE

The successful implementation of a CSE requires a range of enablers and faces several barriers, as noted by various participants across the interviews. Experts highlighted challenges such as regulatory frameworks, commercialization, standardization, and technical complexity, while also identifying key opportunities that could facilitate progress.

R03 elaborates that a thorough understanding of end-of-life processes is needed to transform current linearly designed space systems into circular systems:

> Before beginning my work, I would first want to understand what the product or system is doing in space–whether it's a satellite or something else. Then, I would examine what happens after the service or work is completed. What happens to the system, subsystems, components, and materials once they are no longer needed? Is it simply more cost-effective to dispose them or send them into an orbit where they no longer pose a risk? So, the first important point for me is to understand what is happening with the product or component, or the service once it reaches the end of its life.

R03 adds that another enabler would be to understand the operational limits and specifications of space and the space system itself, as well as the rationale behind its design:

> I think then you would need to understand a bit more about the specifications or limits you have up there. So how could you make sure that different approaches could be applied, and then also at some point, you would need to quickly understand the product design. How does the product in general look? What are the different components you have? How are they connected? Why are they connected like this? I think, if not everything, most things in a product design serve a purpose. Someone, or more than one person, was thinking about why certain elements were needed. For example, batteries use quite a lot of silicon. Why? Because it needs to be resistant to water. It of course hinders and

> complicates disassembly or recycling, but during the design phase, it made sense to ensure water resistance. Understanding the connection between the design–so all the different components, connections, and the product in general–and the reasoning behind choices like materials, fixtures, or other elements is crucial.

Focusing on processing materials in space, R03 explains that recycled material, unlike virgin material, may have potentially diminished qualities, posing a challenge to ensure security:

> For instance, if you have virgin material ... it's easier to ensure that every batch of material or every subsequent batch of components and products is consistent. This is because you can have very precise and strict definitions and specifications for your product and material composition. However, with recycled material, it's quite difficult to ensure that it's always exactly the same. This is because it's nearly impossible to know what someone might have added to the material as an additive, for example. So, security is a very important issue. If something happens in space ... it's much harder to simply go up there and solve the problem. Therefore, we must be aware that we can't neglect security.

R03 further examines the security issue of processing recycled material, illustrating it with a practical example from terrestrial applications:

> This leads to the understanding that recycled material, repaired material, components, or products might not be the same as new ones. For example, bottles made of 100% recycled materials often have a higher scrap rate. It's not because the material is worse, but because it's simply a different material. So, for instance, if you have PET [Polyethylene Terephthalate] and recycled PET, they are not the same material. This means you would need to change your specifications, such as in the case of filling or handling bottles, because the material or component will behave differently.

When transferred to the space context, the challenge of processing and analyzing recycled material must be addressed, in addition to challenges such as the microgravity environment. The expert (R03) then raises concerns regarding the potential impact of other environmental influences in space, suggesting that these factors may lead to material downgrading and pose risks to long-term performance:

> Another concern might be the downgrading of materials based on environmental influences. ... I'm not sure what specific environmental influences space has on materials, but again, it could degrade performance, which is crucial. ... So, if I can put it this way, environmental influences in space might also be a significant risk.

Building on that, R07 highlights the lack of material return experiments to determine the long-term environmental influence on materials:

> [We need] long-term understanding of how the space environment affects materials. Because if you want to have a long duration, like a persistent space platform, you need to understand how it's going to evolve after being exposed to the space environment for that long. And we don't have that many material return experiments, especially long duration ones. Looking at how robotics and mobile systems perform in the long term is important. If you're going to have a persistent circular economy or persistent platforms, you're going to have robotic equipment that's doing a lot of cycling in space, working for a long time. And how do those systems remain reliable over the long term?

When asked about the technical enablers, R07 emphasized the importance of incorporating circular principles in the early design stages, highlighting standardized components, modular construction, and in-orbit servicing technologies as key elements:

> ... I think the standardization of components and interfaces is going to be one of the key enablers. Even before that, the principles of designing satellites to be refurbished and replaced, so the design principles for circularity. So, moving away from current principles of satellite design where you build it, you assemble it, and then it's assembled, and it will be until the end of its life. You'll have this more Lego-style mentality, where you're building subsystems or submodules of a satellite that could be assembled together and taken apart again. So there are interfaces between these individual components and between satellites that need to be standardized. Another technical enabler will be how you build the robotic systems to actually do this assembly

> and disassembly, to do this work in orbit. So, in-orbit servicing, and the development of technologies for that are for sure enablers.

R05 identifies additional technological solutions, while also highlighting a modular design as an enabler:

> Of course, in terms of technologies and interfaces, we need to look at different aspects. There are aspects related to docking, so we will need, for example, different markers to be able to identify the target satellite or different technology onboard to enable capture and docking. Then we will need to think about possibly redesigning the satellites to facilitate something like refurbishment. So, possibly a modular design–a design in which the satellite and each of its subsystems are different modules, where each of the equipment can be easily removed and replaced. Those are all topics of ongoing research at the moment.

When asked about an important technological gap that need to be addressed, R04 responds that:

> I think in the short term, because it could go right into the spacecraft that we are starting to develop now, would be a way of standardizing interfaces without creating overhead. That's very difficult, and it might not always be possible, but there might be ways to have spacecrafts that can be disassembled, similar to the Hubble Space Telescope. That was really pioneering in that sense, and it is also a good example of this kind of partial recycling. Systems that are fully standardized and allow you to put together modules as you like and rearrange them all the time do have a very large overhead, which I think is currently, at least for Earth orbit, a showstopper.

In turn, R06 argues that it may not be possible without adding overhead to projects:

> ... it needs to be looked at from different levels. From a technology point of view, we need clear requirements and interfaces to minimize additional costs and risks. The reason CubeSats were successful is not just because they were small, but because of the standardized container, the launch dispenser. The CubeSat manufacturers and developers did not have to worry about the interface between the satellite and the launch vehicle, as that was all part of the dispenser. They only needed to fit it into the box, which simplified the interfaces greatly. Similarly, for circular economy principles, we need clear interfaces for docking mechanisms, deorbiting sails, and other components. We also need clear requirements for space debris mitigation, such as how many years after the end of a satellite's lifetime it is allowed to remain in orbit. However, achieving this without additional overhead is challenging, maybe not possible. Additionally, from a regulatory point of view, not everyone may want to comply, so it's important to make it as attractive as possible.

Since R06 introduced the topic of regulation, R07 outlined potential leaders in regulatory efforts:

> Well, it's a difficult one, I suppose, because to a certain extent the requirements and regulation need to be built around what's possible and around capabilities. So I can see the argument for it being collectively between space agencies and the space industry, like, "Okay, we think this is what we can do. We think this is how it can be done safely." Already there are examples like the Close-Proximity Operations Guidelines that ESA has developed. CONFERS [Consortium for Execution of Rendezvous and Servicing Operations] is a great example, which is an industry-led, originally NASA-supported body for standardization, particularly on in-orbit servicing. So I think there's an argument to be made that the practical requirements, the regulations, the ISO standard equivalent, should probably be industry and agency led. So people who actually know what's possible and in the art of determining what's possible, figure out what's safe, and then make that into the requirements and guidelines. In terms of the regulations and the changes to who's liable, I think it has to be nation-states and bodies like UN COPUOS [Committee on the Peaceful Uses of Outer Space].

However, R07 also sees regulatory challenges ahead:

> Yeah, but that's an interesting one though because then you get into interesting geopolitical divides, the dual-use nature of in-orbit servicing, and you maybe get to have, if the only people who can do these international treaties are nation states, they'll have a defense angle on what's allowable. That's going to be a whole mess.

In that sense, R07 views current space law as unprepared for advanced space operations, illustrating this with a simple example:

> Space law as a whole is kind of from a different era of the space age; it's not currently adequate. So things like having a regulatory framework, say country A builds a component that is launched on a satellite registered in country B from country C and operated by a space servicing satellite from company or country D, how does the liability for all of that work out? And if you build an entirely new satellite in orbit from pieces from five different ones, let's say assembling sub-modules, whose problem is that now? Where's it registered? Who's liable for it? So fixing all of that is thankfully not my job.

Drawing from terrestrial CE regulation developments, R03 shares the observation that companies tend to wait until regulations are in place, as compliance adds cost and complexity to their operations:

> ... I think most companies actually see it as a hindering. So, if you now also need to fulfill a design for recyclability statement, at the moment, I guess most companies would see it as something they need to pay for again. In addition, they need to buy another service; they need to hire another two people to do that. So, I think they still see it as an obstacle at the moment. And that's also why, when talking to companies, if you ask them if they are willing to pay for this service, the answer is, "Ah, let's wait two more years until the regulation is actually in place, then we will do it."

R03 further elaborates on the importance of achieving the right regulatory balance between incentives and penalties:

> And I guess that's very important–that you always try to link these regulations to economic viability. So, making it actually attractive to companies. You could either force someone to do something by not allowing certain things, or you could actually give them some incentive if they do something good. So, if they do good design, give them some money back or give them some other reward, whatever it may be, in order to motivate companies to do something in another way rather than always punishing them if they do something bad. So for me, there are two sides you could actually choose from.

R09 identifies another challenge in the partial adoption of regulatory frameworks:

> If some players adopt circular economy principles and others don't, there could be economic disadvantages for those that do. A lack of international coordination on circularity legislation might create incentives for non-compliance in some regions.

These insights illustrate that while there are significant challenges to achieving a CSE, key enablers like standardization, governmental support, and technical advancements provide a path forward. The balance between regulation, innovation, and economic incentives will be crucial to unlocking the full potential of CSE.

3.5 CSE as an enabler for large space structures

The implementation of a CSE is seen by many experts as a critical enabler for building large-scale space infrastructure, such as SPS and sunshades, which have the potential to address future emission-free energy needs and climate change. These large structures, positioned in an orbit like GEO or at the Sun-Earth Lagrange Point 1 (L1), are complex and resource-intensive, making circular principles essential to their feasibility.

R10 introduces the section by suggesting that high-mass space systems may appear counterintuitive to the goals of a CSE; however, upon closer examination, they may be what enable a CSE in the first place:

> ... intuitively, one might think that large structures in space would be detrimental to the circular economy due to the amount of mass involved. However, if we apply circular economy principles to space, the main challenge with closing the material loop is that mass tends to be distributed across different orbits. It's usually very energetically expensive to move from one orbit to another. This is one of the primary reasons why active debris removal or recycling multiple spacecraft is so unattractive–you'd have to move from one orbit to another, grab a spacecraft, recycle it, and then move to another orbit, which typically consumes a lot of propellant.

R10 continues to explain:

> However, having a lot of mass in one place, like with megastructures or solar power satellites, could actually be an advantage. You could install a recycling facility on the megastructure

> and gradually recycle solar panels that have degraded, or repurpose the material for trusses or other structures. So, upon second thought, I would say that large structures, which concentrate mass in a specific location, might make certain circular economy principles–particularly closing the material loop–more feasible.

In this context, R10 refers to the rebound effect and proposes a potential regulatory solution:

> This links to the so-called rebound effect, meaning that if you increase the efficiency of a space system–in this case, increasing resource efficiency in space by recycling more–you create an incentive to bring more mass into space. Certain megastructures might become much cheaper, or there may be a greater economic incentive to develop them because they're more efficient with large-scale recycling. Yes, this could lead to launching even more mass into space. Typically, for the rebound effect, one measure that can be taken is to define certain threshold values. You could say, "There's a limit to the amount of mass that can be brought into space." In the future, there might be an allocation process, similar to frequency allocation today, where countries or companies are given limits on how much they can launch into space. That could be one way to avoid the rebound effect. But in principle, any measure that increases the efficiency of a system is susceptible to the rebound effect, meaning you end up with more activity than you would have had without the measure.

Another expert, R08, emphasized that the size and value of SPS make them ideal candidates for CE principles, while their high mass enable the economic viability of certain strategies of the CSE:

> I think if you want to reuse or recycle material, you need large systems like solar power satellites–it's definitely not for small satellites. Maybe there's something in between, like larger space stations in LEO or geostationary satellites, but I think what you need are large systems to establish a business case.

Similarly, R05 directly linked the CSE to large space infrastructures:

> We are looking at in-orbit assembly and manufacturing to create large infrastructures in space, such as solar panels and antennas. This approach will significantly enhance the performance of satellites, avoiding the constraints of launcher size. In the context of solar power satellites, circular economy principles will allow us to reuse and refurbish components, making these systems more sustainable.

R07 also sees the CSE as an enabler for large space structures but mentions one potential drawback that could arise:

> I like to think that large investments, large infrastructures will be more circular, will be more taken apart, refurbished, and put back together. ... you'd have the elements of modularity and the in-orbit assembling, for example. ... Technically, it would enable the building of large structures, like telescopes too big to fit inside a fairing. For example, with the James Webb Space Telescope, it had to unfold in a beautiful, origami-like manner, but you could build something much larger if you could assemble it in orbit. As a side note on space-based solar power, because it doesn't get mentioned much, it's an absolute nightmare in terms of dark and quiet skies–like a giant reflecting body.

Another large structure that could be enabled by a CSE is a sunshade in space for mitigating climate change, as envisioned by R06:

> I think a linearly designed sunshade system doesn't make sense, given the scale. It's hard to imagine building something that costs trillions of dollars, only to let it crash into the sun at the end of its life when we could make better use of those resources. I guess the integration of circular economy principles into the sunshade design would come quite naturally, perhaps even as a necessity to make it feasible, but also considering economic factors. There is certainly a need for circular economy-enabling facilities directly in space, perhaps at L1. These facilities could handle refurbishing, recycling, and manufacturing operations, reducing the need to bring materials back to Earth.

Similar to R06, R04 discussed how a circular approach would naturally align with the development of sunshades:

> If you get to the point of building a planetary sunshade, which I think is the most credible business case at the moment for in situ resources, you will automatically have reuse and

> a circular economy because the solar sails you place one and a half million kilometers away or further, when they wear out, have all the necessary materials. You just collect them and bring them to a processing station where everything is separated. It's like what Bob the Builder would do–reduce, reuse, recycle. You take it apart. It might be a space station, manned by a few dozen people, where the more complex tasks requiring human intelligence are performed. A lot of it can be automated, though, especially if you have a process that regularly consumes raw materials, whether lunar or asteroid-derived, and outputs structural elements, at least in a 3D printer fashion. You can then feed in the already-separated materials, much like how recycling is done on Earth with separate bins for iron, aluminum, and other materials.

In summary, experts agree that the CSE has the potential to enable the development and deployment of large-scale infrastructures such as SPS and sunshades. These systems, which are critical for energy production and climate change mitigation, benefit greatly from circular principles like recycling, refurbishment, and reuse, which reduce waste generation, and extend the lifespan of space assets.

4. Conclusions and future work

This study set out to explore how CE principles could be applied to the space sector, particularly in response to the growing concerns around space debris, resource depletion, and sustainability in space. Through interviews with both space industry and CE experts, key insights emerged, highlighting the importance of integrating CE principles early in the space system design process. Both groups of experts emphasized the potential of CE to extend the life of space assets, reduce the frequency of launches, and mitigate environmental impacts by shifting from linear to circular models. These models prioritize the the application CE strategies, including rethink, reuse, repurpose, and recycle over traditional disposal methods.

Several experts interviewed highlighted that CE principles could be particularly effective for large-scale space structures, such as SPS and sunshades in space for climate change mitigation. These systems would be designed for long-term use, require vast amounts of materials and resources, making them ideal candidates for CE approaches. SPS, likely positioned in GEO, and sunshades, potentially located at L1, would occupy spatially and geographically limited, and therefore highly valuable positions in space. Ensuring these critical orbits remain free of debris and available for future use is paramount. Experts emphasized that applying CE principles, such as modular design, in-orbit repair, and material recycling to these structures would not only extend their operational life but also help maintain these precious orbits by minimizing waste and reducing the need for constant replacement. By integrating CE approaches early in the design of such large-scale systems, we can ensure their long-term sustainability while preserving these vital space locations for future generations.

However, implementing CE practices in space faces unique challenges. Experts identified technological complexity, regulation, and the current lack of standardization as significant challenges. Furthermore, while there is growing interest in in-orbit servicing, material recycling, and modular designs, there is still no mature business model to drive large-scale adoption of all available CE practices. Both space and CE experts noted that more collaborative efforts across industries and government institutions will be needed to overcome these hurdles.

This research also revealed that CE principles must extend beyond just space systems themselves and incorporate the broader supply chain, including ground segment logistics and the manufacturing process. This holistic approach could enable the development of a truly sustainable space ecosystem. The findings from this initial interview phase offer a foundational understanding of the potential pathways for integrating CE principles into space, setting the stage for further research and practical implementation.

Moving forward, the next phase of the research will involve expanding the scope of interviews to include a broader pool of experts, particularly those specializing in space law, policy, economics, and in-situ resource utilization. Additionally, the study will include more institutions and experts from different countries to ensure a diverse range of perspectives. There will be a variety of new topics explored (e.g., risks, business models, space resources, future development pathways), and present topics discussed more into detail. The results of this extended study will culminate in a comprehensive journal publication, contributing to long-term space sustainability and ensuring that space remains accessible and viable for future generations.

To conclude, the authors wish to echo the optimism shared by R05, who reminds us that the journey toward a sustainable CSE begins with ambition and vision:

> We need to start positive, of course, create more momentum and try to see where we can go. Best things always start with the dream, right?

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