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Forecasting space sustainability: Technological development and stakeholder roles

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ABSTRACT

This research forecasts the main trends in the sustainable development of space activities by 2040, focusing on critical areas and the influential roles of various stakeholders, including universities, space agencies, SMEs and startups, large private companies, and international organizations. The study employs a three-round Delphi methodology, engaging 63 international experts from academia, industry, and government agencies to reach consensus on the future trajectory of space sustainability. The process combined quantitative Likert-scale questions and qualitative open-ended responses, which were analyzed to assess convergence and stability across rounds. The third round, conducted one year later, captured how expert opinions evolved under changing geopolitical and economic conditions from 2024 to 2025. Key areas of focus include policies, laws, remote sensing, debris management, access to space, and planetary and deep space exploration. One key finding is the growing role that space agencies and large private companies are expected to play in the sustainable development of space activities by 2040. However, expert consensus on the role of universities, public research centers, and international organizations declined between the second and third round, reflecting a structural shift in funding priorities driven by the geopolitical changes of 2024–2025. Experts also anticipate a broad increase in both general and defense-related investment across most technological areas. Finally, the need to strengthen international cooperation through the creation of new international bodies or the reinforcement of existing ones, has emerged as a critical priority, especially in the domain of law and regulation.

1. Introduction

The space sector has experienced rapid, transformative growth over the past few decades, driven by technological advancements, policy changes, and the entry of an increasing number of players. The advent of the New Space Economy (NSE) era represents a pivotal point in this evolution, characterized by the entry of private companies, the reduction in costs for accessing space, and innovative business models that contrast sharply with the traditional government-led space programs of the past [1–3]. This evolution has resulted in a rapidly growing space economy, valued at about 600 billion dollars in 2023 [4,5], and projected to exceed 1 trillion dollars by 2040 [6–8]. This economy encompasses diverse activities, including satellite communications, Earth observation services, and a whole new array of downstream terrestrial services based on satellite-generated data, and emerging sectors such as in-orbit servicing and manufacturing. The NSE has also created an ecosystem in which established governmental organizations like the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA), as well as large corporations, work alongside startups and new firms [9,10]. This integration has accelerated research and development, reduced launch costs, and enabled countries with limited space capabilities to develop their programs [11,12].

Consequently, the global landscape of space activities has become more intricate, with new stakeholders contributing to an ecosystem that values innovation and strategic partnerships. Moreover, space activities have gained in recent years renewed governmental strategic value related to defence and national security applications. The recent geopolitical evolution on a global scale has exerted a significant policy push towards the development of national programs for accessing space and the consolidation of country-level capabilities for managing space assets both in low-Earth orbit and for space exploration [13]. This eventually led to an increase in the defence-driven budget for space at the global scale [14], with notable variations among countries. In 2024, Europe's expenditure on space capabilities for security and defence is about one order of magnitude lower than the US: only 15% of Europe's

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public space budget relates to military purposes, while the global average is about 50% and is increasing. The number of military satellite launches has nearly doubled between 2021 and 2024 [14], leading to a growing number of public-private agreements for technology development and procurement that will likely attract other companies historically operating in the defence industry to space applications. At the same time, it affects the long-term strategies and business models of key players in the field. Moreover, a greater emphasis on defence and security in global public space budgets might have a non-trivial impact on cross-country collaborations in the field.

The growth of space activities, driven by the different factors mentioned above, presents several significant challenges alongside the opportunities it offers. The sustainability of space operations represents one of the most pressing concerns.

The diversification of actors in the NSE has facilitated economic growth by promoting collaboration and competition and has also enhanced awareness of the impact of space activities on sustainability [15]. Space sustainability is the capacity to engage in activities within the context of the space environment while ensuring its preservation for future generations [16]. The concept of sustainability addresses activities both in Space and on Earth and has multiple dimensions [3]. It encompasses environmental protection, e.g., through the mitigation of space debris and responsible satellite deployment [17], economic sustainability to ensure continued financial viability and benefits for the sector, and it also refers to the impact on societies to guarantee the safety and equity of space [18–20].

In this context, it is essential to gain insights into the future trajectory of space activities to identify the primary challenges to their sustainable development and to evaluate the potential role of key stakeholders involved in the NSE.

To investigate future trends in NSE sustainability, this paper presents the findings of a Delphi study involving 63 experts. A three-round survey, comprising both closed-ended and open-ended questions, was conducted to analyze several key areas for the development of the NSE. These included policy and law, as well as areas where technological developments are more relevant, such as debris mitigation, access to space, remote sensing, life support systems (LSSs), habit design, and spacecraft design. The investigation also considered the impact of different stakeholders and highlighted the main issues hindering the advancement of sustainable space activities as perceived by the experts involved.

Given the significance of geopolitical developments, this study also examined experts' perceptions of the influence of defence and security funding on future investments in specific technologies. A 15-year time horizon was adopted to evaluate the anticipated evolution of the sustainability of space activities. The impact was assessed by analyzing changes in responses expected in 2024 and 2025, which are predicted to reflect shifts in the geopolitical landscape. Recent global events, such as the Ukraine conflict, which has accelerated the utilization of commercial space assets in military operations [21], and increasingly protectionist policies in the United States [22], have reshaped strategic priorities within the space industry. These developments have led to increased defence budgets [14], greater reliance on dual-use technologies, and a reorientation of international collaborations towards security concerns [23,24]. Consequently, sustainable development within the New Space Economy must now be understood not solely through technological or regulatory lenses but also by considering these evolving geopolitical and economic factors.

This study is structured as follows: Section 2 presents the research background and the main issues about space sustainability; Section 3 explains the Delphi method employed in the article; Section 4 describes the panel of experts and the results of the survey; finally, Section 5 presents the conclusions and future developments of the work.

2. Research background: sustainability in the space economy

The issue of space sustainability has become increasingly prominent in recent years, following the activities of United Nations & Office For Outer Space Affairs (UNOOSA), and being included in international agreements such as the Artemis Accords [25,26]. Following the classification outlined in Valente et al. [3], we delineated seven key areas of interest: policy, law and regulation, debris, access to space, spacecraft design, remote sensing and data handling activities, as well as life support systems and in situ resource utilization. Each of these primary focus areas is discussed in the following subsections, along with an examination of the influence of geopolitical and defense considerations on their sustainable development.

2.1. Space policy and regulatory framework

One of the main fields of sustainability research concerns the policy and legal aspects of the Space Economy [15,27,28]. The 1967 Outer Space Treaty and most of the international treaties established fundamental principles, including the peaceful use of space, the prohibition of national sovereignty claims, and the concept that space exploration benefits all humanity [25,29]. However, these frameworks were designed during an era when a small number of nations dominated the global political and economic landscape. The emergence of private initiatives in the space sector, the development of satellite mega-constellations, and the potential advent of space tourism and of extraterrestrial resource extraction have highlighted significant weaknesses in the existing regulatory structure [30–32].

The privatization of space activities raises significant concerns regarding equitable access and sustainability. One key issue is the balance between private companies' economic interests and the global public interest. Moreover, there are many disparities between the policies and standards adopted, not only between the public and private sectors but also across nations. Many authors have emphasized the necessity for enhanced international collaboration and the establishment of uniform international standards [33–35]. In addition to established agencies such as NASA and the European Space Agency (ESA), several space organizations have been developed in recent years, particularly in developing countries [11,36,37]. These nations perceive access to space as a means of reducing digital and technological disparities, for instance, by using satellite-based services to provide internet connectivity to remote regions. Satellite constellations do not require substantial infrastructure and have the potential to narrow the digital divide, leading to equitable access to information and technology and, ultimately, fostering economic and social development.

To facilitate international collaboration and support emerging nations, initiatives such as the UNOOSA guidelines are crucial [33,38,39]. Nevertheless, reaching consensus among the various stakeholders, including established space powers, emerging nations, and private enterprises, remains a significant challenge.

2.2. The debris problem

The debris problem is another topic extensively addressed in the space sector. The rapid accumulation of millions of fragments orbiting Earth represents one of the most urgent challenges to the sustainability of space activities. The danger posed by the debris from disused satellites, spent rocket stages, and past collisions is considerable [40]. Furthermore, the advent of satellite mega-constellations has increased the risk of collisions, raising concerns about the potential instigation of the Kessler syndrome, a cascading chain reaction of debris collisions, first hypothesized by Kessler and Cour-Palais [41], which could significantly impact the usability of key orbital regions [42,43]. Simulation studies confirm that the orbital debris population is on a long-term growth trajectory even under business-as-usual mitigation scenarios [44,45]. Economic models extend the original Kessler argument by formalizing the dynamic feedback between debris generation and orbital congestion [46].

Despite the significant challenges posed by space debris, the current measures to address it remain fragmented and insufficient [47]. International guidelines, such as those set forth by the UN Committee on the Peaceful Uses of Outer Space (UNCOPUOS), encourage voluntary practices, including deorbiting satellites upon the end of their operational lifespan [48]. Moreover, the definition of debris property and the associated responsibilities in the event of collisions remain unclear. From a technological perspective, the advancement of active debris removal technologies, including the development of nets, robotic arms, and lasers, has the potential for success [49]. However, these endeavors face significant technical, legal, and economic obstacles [50].

This scenario illustrates what Hardin [51] described as a "tragedy of the commons," wherein individually rational actions, such as unregulated satellite deployment, collectively result in the degradation of a shared resource. The economics literature has formalised this dynamic by modelling Earth orbit as a common-pool resource subject to negative externalities [52]. Within the sphere of orbital activities, the lack of enforceable governance structures and shared accountability encourages free-riding behaviors, whereby participants benefit from orbital access without contributing to its conservation. However, as Ostrom [53,54] demonstrated, such outcomes are not inevitable: communities possess the capacity to self-organize to sustainably manage common-pool resources through mechanisms of trust, reciprocity, and inclusive governance. Building on this perspective, Weeden & Chow [55] proposed a layered policy architecture for orbital sustainability that combines international norms with operator-level coordination. This viewpoint is further supported by Wesel & Lambach [56], who depict space debris as a collective action dilemma within the global commons and argue that its mitigation requires a polycentric governance approach that connects states, private entities, and international organizations through coordinated yet decentralized decision-making.

The establishment of legally binding agreements with enforceable measures, such as mandatory deorbiting or financial penalties for non-compliance, could encourage greater responsible behavior [57,58]. Moreover, investment in technologies to remove debris and in the development of space traffic management systems will be pivotal in reducing the risk of collisions and ensuring the sustainability of orbital environments [15,59].

2.3. Remote sensing and sustainability on Earth

One of the most discussed topics in space literature is the use of satellite remote sensing data to promote sustainable development on Earth [60–62].

Satellite data supports a wide range of applications that improve life on the planet and contribute to building a more sustainable future. For example, innovative and precision agriculture optimizes field efficiency by minimizing waste and enabling informed crop management decisions (e.g., Ref. [63–65]). This research might have a significant impact on emerging countries [66,67]. Remote sensing data provides important insights for environmental monitoring, allowing a deeper understanding of our planet (e.g., Ref. [68,69]). In particular, it plays a pivotal role in addressing the challenges of climate change (e.g., Ref. [70,71]) and promoting the sustainable management of natural resources (e.g., Ref. [72]).

However, issues remain in ensuring broader access to this type of data and in the collaboration between data providers and users. Expanding access to satellite data would accelerate advances in data processing technologies and broaden their applications in various scientific fields (e.g., Ref. [73–75]).

2.4. Space exploration

The literature discusses sustainability in space exploration, focusing on access to space technologies, such as launch vehicles and ground facilities, life support systems (LSS), and spacecraft design for deep space exploration [76–78]. Significant advances have been made in access to space technologies, with reusable launch vehicles such as SpaceX's Falcon series significantly reducing the environmental and financial costs of reaching orbit. These innovations have contributed to more sustainable space exploration. The success of the Falcon 9 rocket, in particular, can be attributed to an innovative, failure-embracing approach that allowed SpaceX to achieve reusability and reduce costs in a way that was previously thought impossible [79]. However, more investment is needed in green propellants and fully reusable rockets to prevent rocket stages from remaining in orbit, reduce space debris, and mitigate atmospheric environmental impact (e.g., Ref. [76,80]). In planetary exploration, minimizing the environmental impact on host planets is a key issue, not only environmentally but also economically. LSS technologies prioritize recycling resources such as water, air, and waste, thus reducing the resupply missions from Earth. Innovations in closed-loop and bio-regenerative systems enable the efficient recycling of resources and minimize the environmental footprint (e.g., Ref. [81, 82]). Space habitats must also be designed for long-term sustainability, incorporating energy-efficient systems such as solar power and the capability to grow food in space. Spacecraft design, whether for long-distance travel or orbiting laboratories like the ISS, is increasingly focused on sustainability. Efforts include minimizing energy consumption, recycling materials, and improving long-term durability and autonomy (e.g., Ref. [83,84]). Advances in propulsion systems, such as electric and nuclear engines, promise more efficient travel to distant destinations (e.g., Ref. [85,86]). Integrating sustainability into the design of technologies and mission concepts is thus essential for the success of long-duration missions, which could pave the way for the next era of exploration of the Moon and, in the long term, Mars [87,88].

2.5. Geopolitics and Defence

During the post–Cold War era, space progressively developed into a strategic domain where geopolitical interests, security considerations, and technological pursuits converge, as new actors and forms of collaboration emerge [89]. Space activities have consistently reflected broader political dynamics rather than constituting a purely neutral field of research. Nevertheless, since the 2020s, emerging dynamics, including commercial rivalry, mega-constellations, and national security policies, have further amplified the strategic nature of space, rendering sustainability an essential concern [90].

In this recent period of increasing international instability, achieving technological independence has become crucial for maintaining national sovereignty and ensuring the continued operation of space capabilities. Leading players in the global space sector—the United States, the European Union, and China—are now pursuing parallel, and sometimes competing, paths [90]. The U.S. continues to take the lead, backed by a strong public-private partnership ecosystem exemplified by the Artemis program and the growing role of companies like SpaceX. Meanwhile, China is rapidly advancing toward complete technological self-sufficiency, building infrastructure such as the Tiangong space station and the Chang'e lunar missions, with direct implications for national defense. The European Union, although lagging in some areas, such as independence in access to space, has launched initiatives like Galileo, Copernicus, and IRIS[2] to bolster its technological resilience and cut reliance on external actors, especially in dual-use sectors like navigation, Earth observation, and secure communications [91].

Despite increasing strategic competition, international cooperation remains vital for addressing the complexity and high costs associated with space exploration [89]. However, recent conflicts threaten to undermine this collaboration. For example, the ExoMars mission, originally a partnership between ESA and the Russian space agency Roscosmos, was halted after Russia's invasion of Ukraine [92,93]. The NASA Artemis program, strongly supported by ESA and other space agencies, serves as a model of multilateral space diplomacy, exemplified by the related Artemis Accords. However, achieving success requires continuity despite potential political uncertainties. Recent research also highlights how flagship missions extend beyond scientific goals, influencing international relations, public perception, and security policies, making space a domain of political influence [23].

The growing role of space in defense, including satellite surveillance, encrypted communications, orbital threat detection, and anti-satellite capabilities, further enhances the link between technological independence and national security. Having independent control over space infrastructure is becoming vital for maintaining operational capabilities, deterrence, and international credibility.

3. Method and data collection

3.1. The Delphi method

The Delphi method is widely acknowledged as one of the most useful techniques for collecting insights and data from field experts and deriving expectations on future trends (see for example, the seminal studies of [94–96]; and among more recent cases: [97–99]). The main objective of the Delphi approach is to achieve the largest consensus among the experts on the subject under examination. The main and most common steps in the application of the Delphi method are the following: 1) the selection of a group of experts; 2) the creation and distribution of an initial questionnaire on the investigated topic; 3) the analysis of the responses; 4) a second questionnaire, allowing panelists to reconsider their views based on the group's aggregated responses. In some cases, steps 2-4 are repeated until a pre-determined number of rounds is reached, or a consensus threshold is achieved.

Experts are typically invited to rate a series of statements on a Likert scale. Data are treated anonymously, and numerical responses are aggregated in mean values and measures of dispersion to facilitate interpretation [99,100]. Consensus measurement is commonly determined by calculating percent agreement, usually when a threshold of 65-75% of experts is aligned (Niederberger & Spranger, 2020), or by analyzing response dispersion [101]. In addition, experts are often requested to provide open-ended responses that contribute to framing a more detailed picture, identifying outliers or minority views, and the reasons for dissent. Analyzing free-text responses presents several methodological challenges, but it can also enhance the interpretation of quantitative data (e.g., Ref. [102,103]).

The Delphi method has been employed in numerous studies to evaluate future trends, including recent cases in space exploration and sustainability. These studies have focused on a specific aspect and analyzed the factors hindering or promoting its development. For instance, Aliakbargolkar & Crawley [104] examined in-orbit transportation infrastructure for human space exploration, outlining key aspects, recommendations, and future requirements. Profitiliotis & Haqq-Misra [105] focused on Mars exploration and planetary preservation, addressing economic, commercial, and political challenges related to Martian resource utilization and environmental conservation. Spedding et al. [106] investigated issues surrounding lunar outposts and the technological development of in-situ resource utilization (ISRU), nuclear power, and solar energy to promote an established lunar outpost. Finally, Toivonen [107] explored the sustainability of space tourism, conducting an empirical study on Finnish public perceptions regarding the intersection of space tourism and environmental responsibility. In contrast to the aforementioned studies, which each concentrate on a single theme, this work adopts a more comprehensive approach by examining multiple aspects related to space sustainability and highlighting the role of various stakeholders in fostering sustainable growth within the sector.

3.2. Preliminary activities and selection of experts

During the first months of 2024, the preliminary arrangements to prepare the Delphi survey were started: after the identification of relevant topics, the experts were selected, the questionnaire was developed, and then tested to guarantee clarity to the participants.

Concerning the identification of topics, we relied on literature on space sustainability [3,15,108]. The topics of interest can be grouped in seven main clusters, which will represent the corresponding sections of the questionnaire: sustainability in policy and law, debris mitigation technology, access to space technology, remote sensing activities, LSSs and in situ resource utilization, spacecraft design, and Geopolitics and Defence.

Several sources were employed to select the panel of experts. The identification process involved contacting the experts via email, with addresses obtained from 1) members of IAF committees, 2) principal investigators featured in projects collected in TechPort, 3) experts were contacted via the professional networking platform LinkedIn, 4) the founders of startup enterprises operating within the space sector, identified and sourced through the Dealroom platform and 5) the authors' personal contacts. This resulted in the collection of approximately 950 contacts. A Google Form was created to obtain the willingness of the potential experts to participate in the study. Additionally, experts were contacted passively through the posting of a call for participation on the LinkedIn page of the Italian Association of Aeronautics and Astronautics (AIDAA), which gathers 4000 contacts, including professors, researchers, and experts in the space sector, primarily Italian but also international. Furthermore, the call for participants was posted on the Telegram channels of the Space Generation Advisory Council (SGAC), a community of over 29,000 young space professionals). In the call for participation, all applicants were required to declare that they had at least three years' experience in the field to meet the selection criteria.[1]

These activities led to the identification of 63 individuals who expressed their willingness to participate in the study and declared to have at least three years of experience in space-related activities. This preliminary response rate is estimated to be approximately 6%. This group of experts constituted the panel for the rounds of the survey.

3.3. Structure of the questionnaire and dissemination

The questionnaire was initially distributed to a limited number of participants to identify ambiguous questions. However, no significant issues were identified, confirming the clarity and relevance of the proposed questions.

The questionnaire was deployed in three rounds to examine the trajectory of sustainability in space over the coming years and identify the key stakeholders for sustainable development. Two types of questions were included: closed and open-ended. The closed questions were designed using a Likert scale, ranging from 1 to 5. A point of comparison with the existing situation was established by repeating closed questions, focusing on both the present and prospective scenarios for 2040. 2040 is significant for space sustainability due to global efforts to address the space debris problem, achieve net-zero emissions in space activities, implement UN sustainability guidelines, and binding international treaties (e.g., Refs. [4,92,93,108]). The open-ended questions allowed participants to provide further insights and details into their responses and to present their perspectives on the main challenges to sustainable development in each area of investigation. Recurrent themes found in the open-ended responses of the first round were also included as new questions in the second round.

The questionnaire consisted of three main parts, as depicted in Table 1. The first, which focuses on policy and legal aspects, asked

[1] The passive method estimates a pool of 6000 receivers who might overlap with the actively reached contacts.

Table 1
Survey structure.

Part 1	
Space Policy	Q1 Sustainability pillars for space policy
Space law and regulations	Q2 Sustainability pillars space law
	Q3[a] Factors that impact sustainability in policies and laws
Part 2	
Debris	Q4 Issues related to debris mitigation
	Q5 Stakeholders' role in the sustainable development of debris mitigation technology
	Q6 Issues related to the sustainable development of debris mitigation technology
	Q7[a] Factors related to debris mitigation and sustainable development of debris mitigation technology
Access to space technology	Q8 Stakeholders' role in the sustainable development of access to space technology
	Q9 Issues related to the sustainable development of access to space technology
Spacecraft design	Q10 Stakeholders' role in the sustainable development of spacecraft design
	Q11 Issues related to the sustainable development of spacecraft design
	Q12[a] Factors impacting the sustainable development of spacecraft design
Remote sensing and data handling activities	Q13 Stakeholders' role in the sustainable development of remote sensing activities
	Q14 Issues related to the sustainable development of remote sensing activities
	Q15[b]**Which stakeholder do you think will be the main driver of development in the following sub-areas of Remote Sensing in the next 15 years?
LSS and habitat design	Q16 Stakeholders' role in the sustainable development of remote sensing activities
	Q17 Issues related to the sustainable development of remote sensing activities
	Q18[a] Factors impacting the sustainable development of LSSs and habitat design
Part 3	
Geographical leader area	Q19[b] Considering your previous answers, which geographical area do you expect to lead technological development in each of the following fields?
Private and Public investments	Q20[b] Looking at the global scenario, will public and private investment in the following technological areas decrease or increase in the next 15 years?
Investments in Defense and Security	Q21[b] Considering the global scenario, do you expect public and private Defence & Security investments will have an impact on the development of space technology in the next 15 years?

[a] Questions added after the first round, from the analysis of the open-ended questions.
[b] Questions added in the third round.

respondents to indicate the extent to which space policies and laws facilitate the promotion of each environmental, economic, and social sustainability aspect. In addition, the open-ended question asked participants to identify the main problems in developing space policies and legislation that would be more supportive of sustainability. The second part of the questionnaire examines the roles of various stakeholders in the sustainable development of different technologies. Respondents were invited to indicate the importance of each stakeholder (i.e., large and private companies, small and medium-sized enterprises (SMEs) and startups, university and public research centers, government organizations, and international institutions) in the sustainable development of space technology or the activity under investigation. Furthermore, in the open-ended questions, respondents were invited to highlight the main challenges associated with the sustainable development of each technology. Finally, the third part examined geopolitical aspects and the interplay with defense investment.

The responses of the first round were collected in the period from April to mid-May 2024. After the initial invitation, two fortnightly reminders were sent to the experts involved (the same approach was applied in all rounds of survey deployment). The second round lasted between mid-June and July 2024. Table 2 shows the number of experts who participated in the three rounds (with a response rate of 70%, 63% and 55% on the size of the panel, respectively).

After the first round, the results were analyzed to identify consensus in the closed-ended questions: questions that did not achieve consensus were submitted again in the second round. Further details regarding the consensus criteria can be found in Section 3.4. The second objective is to analyze the open-ended questions to identify any significant insights and, subsequently, to consider introducing additional themes for the second round. Open-ended responses were analyzed thematically: recurring issues raised by multiple respondents were identified, and where they pointed to a specific researchable question, they were incorporated as new closed-ended items in the subsequent round. For instance, the frequent observation that stricter sanctions could promote more sustainable practices in space policy and law led to the inclusion of a dedicated closed-ended question in the second round. Themes that reflected a broad consensus, such as the importance of international collaboration, were instead reported as contextual findings rather than converted into survey items. Indeed, the comments on the sustainable development of space activities highlighted pivotal factors in the following areas: policy and legislation, debris mitigation, life-support systems (LSS) and habitat design, and spacecraft design. These factors were investigated in the second round, using additional closed-ended questions. It is important to note that when divergent opinions were expressed in the open-ended question, both were considered, and the totality of the panel's opinion was investigated. For instance, respondents advocated that implementing international policies could promote more sustainable practices. In contrast, another group preferred the establishment of national policies and a reduction in centralized governance as actions to promote sustainability. In these cases, both opinions were considered. Finally, the third round was conducted to investigate whether the experts' opinions had changed after one year, considering the geopolitical scenario, and to assess the influence of private and public investments, as well as investments in defense and security, on sustainable and technological development in the space sector.

Based on the expert feedback and the answer rate, it was concluded that achieving a high response rate for several additional Delphi rounds would be challenging. Given the high stability and consensus observed in the close-ended questions and the ability to draw relevant conclusions from the open questions, the authors decided to terminate the study after three rounds.

3.4. Consensus criteria

The definition of consensus in closed-ended questions is based on three measures: the interquartile range (IQR), the polarization of responses, and the mean value. The IQR, defined as the difference between the lower quartile (Q1) and the upper quartile (Q3), is a widely used metric to measure consensus in Delphi studies [100]. According to this criterion, considering a Likert scale from 1 to 5, the consensus is reached when the IQR is less than 1. The secondary criterion, the percentage of responses at each of the two poles is utilized to evaluate the polarization of reactions towards one extreme. Indeed, the 5-point Likert scale ranges from very negative to very positive, and each question is evaluated. The consensus is reached when the sum of positive and very positive responses, or the sum of negative and very negative responses, exceeds the

Table 2
Number of responses collected in each round of the survey.

Round	Survey delivery period	Responses
1	From April to mid-May 2024	44
2	From mid-June to July 2024	40
3	From April to mid-May 2025	35

threshold of 65%. The mean is utilized to ascertain consensus when the two criteria yield divergent outcomes. Specifically, consensus is determined when the mean exceeds 3.5 or is below 2.5.

4. Results and discussion

This section presents the panel description and the study's primary results. Specifically, it reports the experts' opinions on the evolution of space sustainability for each macro area under investigation, highlighting the discrepancy between the current situation and the projected evolution by 2040. Moreover, the main issues to sustainable development in each area are outlined, as identified through the open-ended questions.

4.1. Delphi expert panel

63 experts in the space industry agreed to participate in this study. The expert panel included professionals with a range of expertise that includes space technology, environmental science, policymaking, and industry leadership, from diverse backgrounds as evidenced by their affiliations (Fig. 1). More than 30% of the experts have over two decades of experience, and the panel includes senior, mid-career, and junior profiles. To illustrate typical expertise levels, anonymized examples include: the Head of Commercialisation at a major intergovernmental space agency, with over twenty years of experience in space policy, debris, and security; a Senior Scientist at a national aerospace research centre, with more than ten years of work on life support systems, in-situ resource utilization, and in-orbit services; and a Technical Project Manager at a European university space centre, specializing in innovative materials and space instrumentation. Table 3 provides a breakdown of the panel's professional roles.

This diversity ensured that panelists offered a comprehensive perspective on the sustainability challenges and opportunities within the space sector.

Table 4 presents the experts' geographical distribution, indicating that 68% of them are from Europe, while 20% are from North America. To a lesser extent, the experts come from various Asian, Oceania, and South American countries.

The gender distribution presented in Table 5 reveals that around a third of the experts are female.

Table 3
Composition of experts' panel across professional roles.

Main role	% of experts
Top Manager	33
Academic	17
Technical professionals	17
Space Agency	21
Consulting	11

Table 4
Geographical distribution of the experts' panel.

Country/State	% of experts
Europe	68.3
North America	20.6
South and Centre America	4.8
Asia	3.2
Oceania	3.2

Table 5
Gender distribution of the experts' panel.

Gender	% of experts
Female	31.7
Male	65.1
Not relevant/prefer not to say	3.2

4.2. Sustainable development of space activities toward 2040

This section presents the study's findings following the third round of investigation for each topic. The third round was administered in 2025, a year after the second round. The results of the second round are reported in the Appendix for comparison.

4.2.1. Space policy and law

The first macro area examined the presence of policies, laws, and regulations that promote sustainability in space across the three key pillars: economic, environmental, and social sustainability. This part includes three questions.

Q1: Do "Space Laws and Regulations" encourage sustainable practices, considering environmental, social, and economic factors, today? And in 2040?
Q2: How effectively are "space policies" supporting the sustainability of space activities in terms of the environment, economy, and society in the present day? And in 2040?
Q3: Please rate the effectiveness of these initiatives for the sustainable development of "Space Law and Regulations" and "Space Policy" up to 2040.

The findings for Q1 and Q2 are summarized in Tables 6 and 7, respectively. On Law and Regulation, there is a consensus on the importance of both environmental and social sustainability. Experts specifically note that existing legislation does not sufficiently prioritize sustainability in these areas. Likewise, there is consensus that current policies fail to support environmental sustainability adequately.

Looking ahead to 2040, the second-round survey revealed that 67% of respondents anticipated a significant increase in focus on environmental sustainability (responses from round two are in the Appendix). However, this agreement weakened when the same question was asked again a year later in the third round (see Table 6). The consensus in the second round reflected ongoing efforts by space agencies to advance international policies and treaties, such as addressing space debris and supporting collaborative initiatives, such as the Artemis Accords for lunar exploration. By the third round, expert opinions had become more uncertain. This change highlights growing concerns over unresolved

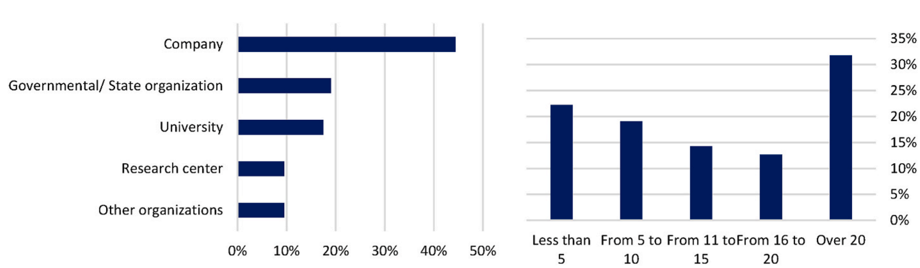

Fig. 1. Affiliations of experts' panel (left) and years of experience of the experts (right).

Table 6
Results for Q1: Do "Space Laws and Regulations" encourage sustainable practices, considering environmental, social, and economic factors, today? And in 2040?

	Law and regulation											
	Today						By 2040					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Environmental sustainability	2.2	1	62.9	28.6	8.6	Yes	3.2	2	28.6	22.9	48.6	No*
Social sustainability	2.2	2	65.7	22.9	11.4	Yes	2.9	2	37.1	31.4	31.4	No
Economic Sustainability	2.4	2	51.4	31.4	17.1	No	3.1	2	34.3	22.9	42.9	No

Note: Consensus was reached on the environmental pillar in the second round. Between the second and third round, consensus was lost on environmental sustainability, indicated by *.

Table 7
Results for Q2: How effectively are "space policies" supporting the sustainability of space activities in terms of the environment, economy, and society in the present day? And in 2040?

	Space Policy											
	Today						By 2040					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Environmental sustainability	2.5	1	57.1	22.9	20.0	No	3.3	1	22.9	25.7	51.4	No*
Social sustainability	2.4	1	57.1	34.3	8.6	Yes	2.9	2	28.6	45.7	25.7	No
Economic Sustainability	2.7	1	31.4	57.1	11.4	No	3.4	1	17.1	34.3	48.6	No

Note: consensus was reached on the environmental pillar in the second round. Between the second and third round, consensus was lost on environmental sustainability, indicated by *.

externalities, such as orbital debris, atmospheric pollution, and the overuse of LEO, which necessitate complex regulatory solutions within a fragmented geopolitical landscape. Finally, regarding economic and social sustainability, the expert's opinion is inconsistent.

In the comment section, the panel identified several challenges that hinder the development of sustainable space policies and laws. Specifically, the lack of international standards and discrepancies between national laws and outdated international agreements are key barriers. The current frameworks reflect an old era dominated by a few nations, leading the sector and failing to account for the diverse stakeholders in the space industry, including emerging nations and private companies. Another major challenge is the lack of sufficient incentives to adopt sustainable practices, which slows innovation, especially for startups and emerging nations that face higher costs and technological hurdles when developing sustainable solutions. As shown in Table 8, experts agreed on the importance of strengthening legislative and regulatory frameworks at both national and international levels, and of supporting improvements to existing international bodies rather than creating new ones. Comparing the second and third rounds, while international organizations remain important for advancing sustainability, their perceived effectiveness has decreased, indicated by a drop in the average rating from 4.0 to 3.5. Additionally, opinions diverged on the introduction of stricter sanctions. Therefore, experts believe that future efforts should focus on international cooperation and modernizing legal frameworks to effectively address these challenges in the evolving space exploration sector.

4.2.2. Debris mitigation

The investigation into debris mitigation was conducted from two perspectives: policy (Q4) and technological (Q5 and Q6). Furthermore, key challenges and potential mitigation strategies that emerged in the first round were presented to experts during the second survey round (Q7). The questions in this section evaluate the experts' opinion on issues and potential mitigation initiatives (Q4, Q6, and Q7), and explore the role of the main stakeholders in the NSE (Q5).

> Q4: Considering the problem of "space debris", what are the most critical issues in developing effective policies up to 2040?
> Q5: Considering the technologies for "debris mitigation", please rate the importance of the following stakeholders in supporting sustainable development.
> Q6: Considering "debris mitigation" technologies, what are the most critical issues for sustainable development up to 2040?
> Q7: Please rate the impact of the following factors in mitigating "space debris" and supporting sustainable space activities up to 2040.

Table 8
Results for Q3: Please rate the effectiveness of these initiatives for the sustainable development of “Space Law and Regulations” and “Space Policy” up to 2040.

	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Strengthening of National legislative/regulatory bodies	3.7	2	22.9	8.6	68.6	Yes
Strengthening of International legislative/regulatory bodies.	3.5	1	22.9	11.4	65.7	Yes
Creation of New International bodies.	3.0	2	40.0	20.0	40.0	No
Introduction of more severe sanctions.	3.0	2	34.3	28.6	37.1	No

From a technological perspective, there is consensus on the important role that space agencies and large companies currently play in debris mitigation, as shown in Table 9. However, opinions vary regarding the roles of other stakeholders. Looking ahead, the panel agrees that large companies, start-ups, SMEs, and space agencies will dominate the development of sustainable debris-mitigation technologies. Companies are already creating markets for services like debris removal, end-of-life disposal, and life-extension technologies. These efforts are essential, as space debris poses a collective challenge for the global space community. In contrast, experts are divided about the future involvement of international organizations, universities, and research centers. Notably, a year ago, the panel believed these stakeholders would have a significant role; today, that confidence has decreased. This change reflects increasing uncertainty, likely driven by policy trends that prioritize private sector leadership over academic and research contributions. For international organizations, the decline in consensus is mainly due to rising geopolitical tensions and the rise of more nationalist policies, both of which have weakened global cooperation and reduced the effectiveness of these institutions.

Table 10 shows that experts agree that enhancing debris mitigation sustainability depends on developing fully reusable systems and increased investment in natural deorbiting methods. These strategies should be integrated into the mission from the earliest stages of development. For example, incorporating atmospheric drag augmentation systems or adopting more advanced procedures, such as autonomous relocation to graveyard orbits, should be planned from the outset. In parallel, there is a strong need to improve debris-tracking technologies, though experts remain divided on how best to manage and implement mapping solutions for space debris monitoring.

From a political perspective, insights derived from questions Q4 and Q6 reveal two primary concerns emphasized by the experts. Firstly, the lack of standardized international regulations and guidelines has resulted in fragmented national strategies. No governmental body or space agency has assumed responsibility for establishing binding global regulations. Consequently, existing legal frameworks tend to be weak, ambiguous, and non-compulsory, which deters investment in sustainable practices. Secondly, developing near-zero debris systems requires substantial funding; however, many stakeholders are reluctant to invest. This hesitation reflects a broader dynamic characterized by negative externalities and insufficient private incentives, whereby individual actors internalize the costs of sustainable behaviour while the benefits are distributed collectively. In this context, the governance of orbital space mirrors the phenomenon Hardin [51] described as a “tragedy of the commons,” in which rational individual decisions aimed at cost minimization lead to the collective deterioration of a shared environment. This free-rider mentality and diffusion of responsibility continue to hinder coordinated efforts toward sustainable space operations. Overall, the panel emphasizes that without a more substantial political commitment, aligned incentives, and effective international coordination, progress toward sustainable space governance will remain slow and uncertain.

4.2.3. Access to space technology

“Access to space” is defined in this study as the range of activities and technologies that enable humanity to reach and operate within the space environment. This encompasses carrier technologies, such as launchers and spacecraft, as well as the infrastructure on Earth, including spaceports, launch sites, and ground control centers. Space access is strategically important for a nation, as it enables independence in critical areas such as national security, telecommunications, navigation, and weather monitoring. Furthermore, access to space fosters innovation, stimulates economic growth, and enhances a nation's global influence [109].

An increasing number of nations are developing their own infrastructure to launch satellites into orbit or are relying on other nations to do so. Concurrently, the imperative for sustainability is intensifying. Given these considerations, the experts have asked Q8 and Q9.

> Q8: Considering "Access to Space" technologies, please rate the importance of the following stakeholders in supporting sustainable development.
> Q9: Considering "Access to space" technologies, what are the most critical issues for sustainable development up to 2040?

The findings for Q8, presented in Table 11, indicate that experts view space agencies, large companies, start-ups, and SMEs as key players in promoting sustainable access-to-space technologies. Looking toward 2040, they do not expect notable changes in stakeholder roles. Nonetheless, there is a growing acknowledgment of the significance of SMEs and start-ups, as indicated by their rising average score from 3.6 to 4.0. Conversely, opinions remain divided on the involvement of universities, research centers, and international organizations in this area.

Analysis of expert responses to Q9 shows that advancing sustainable space technology hinges on overcoming major challenges in the launch sector. The rocket market currently lags behind growing demand, creating a significant mismatch between supply and demand. This gap keeps payload costs high, limiting wider access to space. From a sustainability perspective, increased investment is needed in green propellants and environmentally friendly combustion materials. A key element of sustainability is enhancing reusability in launch systems,

Table 9
Results for Q5: Considering the technologies for "debris mitigation," please rate the importance of the following stakeholders in supporting sustainable development.

	Debris mitigation technology											
	Today						By 2040					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Large private companies	3.7	2	17.1	17.1	65.7	Yes	4.2	1	8.6	5.7	85.7	Yes
SMEs and startups	3.4	1	17.1	25.7	57.1	No	3.9	2	11.4	14.3	74.3	Yes
Space agencies, national and intergovernmental bodies	4.2	1	8.6	2.9	88.6	Yes	4.1	1	8.6	8.6	82.9	Yes
Universities and public research centers	3.1	1	22.9	42.9	34.3	No	3.5	1	20.0	28.6	51.4	No*
Other international organizations	3.0	2	37.1	25.7	37.1	No	3.5	1	22.9	28.6	48.6	No*

Note: Between the second and third rounds, consensus was lost for some stakeholders, as indicated by *.

Table 10
Results for Q7: Please rate the impact of the following factors in mitigating "space debris" and supporting sustainable space activities up to 2040.

	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Technological improvements for full-reusability spacecraft.	3.8	1	3.4	31.0	65.5	Yes
More investments in natural deorbiting systems.	3.9	2	6.9	24.1	69.0	Yes
The improvements in debris-tracking technologies.	3.8	2	13.8	17.2	69.0	Yes
Support the creation of a single centralized mapping managed by a public body.	3.5	1	10.3	37.9	51.7	No
Support multiple players (public and private), each with its own mapping approach.	3.2	1	24.1	37.9	37.9	No
Reduce the influence of launcher manufacturers on regulatory bodies dealing with debris to avoid conflicts of interest.	3.5	2	13.8	24.1	62.1	No

Table 11
Results for Q8: Considering "Access to Space" technologies, please rate the importance of the following stakeholders in supporting sustainable development.

	Access to space technology											
	Today						By 2040					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Large private companies	4.3	1	5.7	2.9	91.4	Yes	4.3	1	11.4	0.0	88.6	Yes
SMEs and startups	3.6	1	17.1	22.9	60.0	Yes	4.0	1	11.4	5.7	82.9	Yes
Space agencies, national and intergovernmental bodies	4.2	1	5.7	8.6	85.7	Yes	4.2	1	11.4	2.9	85.7	Yes
Universities and public research centers	3.1	2	34.3	28.6	37.1	No	3.1	2	34.3	25.7	40.0	No
Other international organizations	3.0	2	42.9	22.9	34.3	No	3.1	2	40.0	20.0	40.0	No

which helps lower costs and reduces the environmental impact of space activities. Reaching this goal relies on increased investment in research and development. Effective enforcement mechanisms in both the public and private sectors are crucial in promoting these innovations.

4.2.4. *Spacecraft design*

Another area of technology that has been studied is sustainable spacecraft design. In the first round, questions Q10 and Q11 were used to explore stakeholders' roles and the main issues in sustainable development. In the next round, question Q12 was based on the answers to question Q11.

Q10: Considering technological advancements in "Spacecraft", please rate the importance of the following stakeholders in supporting sustainable development.
Q11: Considering technological advancements in "Spacecraft," what are the most critical issues for sustainable development up to 2040?
Q12: Please rate the impact of the following factors in "Spacecraft" to favor the sustainable development of Space activities up to 2040.

As shown in Table 12, most experts agree that large companies and space agencies currently dominate this area. However, opinions on other stakeholders are varied. Looking ahead to 2040, experts anticipate that SMEs, universities, and research centers will also play significant roles in the sustainable development of spacecraft design, alongside space agencies and large companies. Conversely, the panel is divided on the

Table 12
Results for Q10: Considering technological advancements in "Spacecraft," please rate the importance of the following stakeholders in supporting sustainable development.

	Spacecraft Design											
	Today						By 2040					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Large private companies	4.2	1	5.7	8.6	85.7	Yes	4.4	1	2.9	2.9	94.3	Yes
SMEs and startups	3.5	2	22.9	22.9	54.3	No	4.1	1	5.7	14.3	80.0	Yes
Space agencies, national and intergovernmental bodies	4.3	1	2.9	14.3	82.9	Yes	4.3	1	11.4	0.0	88.6	Yes
Universities and public research centers	3.3	2	28.6	22.9	48.6	No	3.6	1	17.1	20.0	62.9	Yes
Other international organizations	2.5	3	54.3	20.0	25.7	No	2.8	3	45.7	17.1	37.1	No

role of international organizations; their opinions are entirely inconsistent.

Analysis of the open-ended responses to Q11 uncovered several key factors that could support the sustainable development of spacecraft design. These factors were then evaluated in Q12 to determine the level of agreement among experts, as shown in Table 13.

The panel only agreed on the importance of developing more autonomous and intelligent systems, as they are seen as essential for enhancing mission efficiency, ensuring safer operations, and ultimately reducing costs. However, there was no agreement on the other factors. Overall, the findings demonstrate strong agreement on the value of intelligent and autonomous technologies but also highlight differing opinions on other strategic and technical issues. This absence of consensus might reflect broader uncertainties about future priorities and varied stakeholder viewpoints, as well as the roles these measures could have in supporting sustainable space exploration and utilization.

4.2.5. *Remote sensing and data handling activities*

As previously discussed, the utilization of satellite data to promote sustainability and enhance our understanding of Earth phenomena has become a prevalent practice. The questions below have been submitted to investigate the role of the stakeholders in this area.

Q13: Considering "Remote sensing and Data handling" activities, please rate the importance of the following stakeholders in supporting sustainable development.

Q14: Considering "Remote sensing and Data handling" activities, what are the most critical issues for sustainable development up to 2040?

Q15: Which stakeholder do you think will be the main driver of development in the following sub-areas of Remote Sensing in the next 15 years?

Table 14 shows that experts largely agree on the significant contribution of large companies, space agencies, SMEs, and startups to the sustainable development of remote sensing activities. Looking towards 2040, these stakeholders are expected to remain influential, while universities and research centers are anticipated to become more important collaborators. However, there is no consensus on the future role of international organizations, indicating uncertainty about their ability to impact technological and regulatory developments in the evolving geopolitical environment.

To examine these dynamics more thoroughly, experts responded to Q15, which targeted specific subfields within remote sensing, such as Earth Observation (EO), telecommunication, and navigation. The aim was to more accurately evaluate stakeholder influence in each area. As shown in Table 15, experts identified space agencies and large companies as the main drivers of technological advancement in both navigation and EO. Conversely, in the telecommunications subsector, large companies are expected to lead future advancements. This distinction mirrors broader trends in the space industry. Navigation and EO activities often imply long-term strategic objectives, security concerns, and significant public funding—areas where space agencies play a key role alongside industry partners. In contrast, the telecommunication sector has shifted toward being a highly commercial field, marked by rapid innovation, market-driven constellation deployments, and active private investment. This is why major companies are predominantly influential in this sector, while governments primarily serve as regulators or facilitators rather than directly implementing technologies.

In Q14, the primary issues concerning the sustainable development of remote sensing activities were evaluated. A key finding is the urgent need to improve data democratization and sharing, as well as the importance of fostering international collaboration to achieve this goal. Such collaboration is vital for ensuring data accessibility benefits the global space community and encourages equitable progress. Technologically, congestion in LEO has become a significant concern, highlighting the need for an efficient system to improve space situational awareness (SSA). The growing number of satellites in LEO complicates orbital management and raises collision risks, making advanced tracking and coordination systems essential. An additional challenge is the high financial barrier to accessing GEO, which demands substantial investment in advanced observational instruments for effective operation, especially compared to LEO satellites. To tackle these issues, investing in technological advancements is crucial for reducing costs associated with GEO access and operations, while alleviating congestion in LEO.

4.2.6. *Life support systems and in situ resource utilization*

The domain of technology for life support systems and in situ (ISRU) resource utilization encompasses all technological solutions designed to facilitate human operations in space and on the surface of a planet, as well as those technologies employed to extract resources from a planet for the benefit of astronauts and scientific research. One example of such a resource is regolith, which is used for radiation shielding and for collecting samples to investigate the planet's composition. The present study has analyzed sustainable development in this domain and the role of stakeholders by posing Q16 and Q17 to experts in the first round and Q18 in the second.

Q16: Considering technologies for "Life support system and ISRU", please rate the importance of the following stakeholders in supporting sustainable development.

Q17: Considering technologies for "Life support system and ISRU", what are the most critical issues for sustainable development up to 2040?

Q18: Please rate the impact of the following factors in "LSS system and ISRU technologies" on sustainable space development up to 2040.

As shown in Table 16, experts agree that space agencies and large companies currently lead the sustainable development of life support systems (LSSs). By 2040, universities, research centers, SMEs, and startups are also expected to become key players. This expected growth is likely to reflect rising expectations for space tourism and the development of private and commercial space stations in the future. Like the International Space Station (ISS), these stations will need advanced life support systems to guarantee human safety and well-being in space.

Expert opinions on the role of international bodies remain divided. This split likely stems from these organizations' limited involvement in the design and development of LSS technologies. Their influence primarily centers on establishing regulatory standards and guidelines rather than directly fostering innovation or implementation.

Table 13
Results for Q12: Please rate the impact of the following factors in “Spacecraft” to favor the sustainable development of Space activities up to 2040.

	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Technological advancements in radiation protection systems.	3.7	2	18.5	22.2	59.3	No
The development of more autonomous and intelligent systems.	4.3	1	7.4	7.4	85.2	Yes
Development of Space-Based Solar Power technology.	3.5	2	22.2	25.9	51.9	No
Development of space weather monitoring.	3.3	2	25.9	25.9	48.1	No
Relax the requirements on technological readiness.	3.3	2	59.3	29.6	11.1	No

Table 14
Results for Q 13: Considering "Remote sensing and Data handling" activities, please rate the importance of the following stakeholders in supporting sustainable development.

	Remote sensing and data handling activities											
	Today						By 2040					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Large private companies	4.1	1	2.9	11.4	85.7	Yes	4.3	1	5.7	5.7	88.6	Yes
SMEs and startups	3.9	1	14.3	8.6	77.1	Yes	4.2	1	5.7	5.7	88.6	Yes
Space agencies, national and intergovernmental bodies	4.4	1	2.9	2.9	94.3	Yes	4.4	1	5.7	0.0	94.3	Yes
Universities and public research centers	3.8	2	11.4	25.7	62.9	No	3.8	2	17.1	11.4	71.4	Yes
Other international organizations	3.1	2	40.0	17.1	42.9	No	3.3	3	40.0	8.6	51.4	No

Table 15
Results for Q15: "Which stakeholder do you think will be the main driver of development in the following sub-areas of Remote Sensing in the next 15 years?"

	Large private companies	SMEs and startups	Space agencies, national and intergovernmental bodies	Universities and public research centers	Other international organizations	Total
Navigation	37.1	11.4	34.3	5.7	11.4	100.0
Earth Observation	31.4	14.3	40.0	8.6	5.7	100.0
Telecommunication	68.6	11.4	5.7	5.7	8.6	100.0

Table 16
Results for Q15: Considering technologies for "Life support system and ISRU," please rate the importance of the following stakeholders in supporting sustainable development.

	LSSs and habitat design											
	Today						By 2040					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Large private companies	3.6	1	8.6	37.1	54.3	Yes	4.1	1	8.6	5.7	85.7	Yes
SMEs and startups	3.7	2	14.3	28.6	57.1	No	4.1	1	5.7	14.3	80.0	Yes
Space agencies, national and intergovernmental bodies	4.4	1	5.7	0.0	94.3	Yes	4.4	1	5.7	5.7	88.6	Yes
Universities and public research centers	3.7	2	14.3	22.9	62.9	No	3.8	2	14.3	17.1	68.6	Yes
Other international organizations	2.6	3	57.1	8.6	34.3	No	2.9	2	45.7	17.1	37.1	No

Following a thorough analysis of the issues discussed in Q16 and reassessed in Q17, experts emphasized the vital importance of technological advancements in promoting sustainable space development of LSS and ISRU technologies (refer to Table 17). Among the most impactful factors is the improvement of closed-loop systems, although no consensus was reached. These systems aim to recycle waste, such as transforming urine into drinkable water on the International Space Station (ISS), and greatly diminish the need for resupply missions from Earth. While more complex technically than open-loop systems, closed-loop solutions are deemed critical for supporting long-term missions and deep space exploration. Notably, bio-regenerative closed-loop systems represent a significant improvement, enabling the autonomous

Table 17
Results for Q17: Please rate the impact of the following factors in "LSS system and ISRU technologies" on sustainable space development up to 2040.

	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Scalability of technologies (larger or new market).	4.1	1	11.1	11.1	77.8	Yes
International collaboration.	3.8	2	14.8	22.2	63.0	No
In-orbit servicing, recycling, and manufacturing in space.	4.0	1	7.4	14.8	77.8	Yes
Development of bio-regenerative life support systems.	4.0	2	11.1	25.9	63.0	No
Developments in new energy generation, e.g., nuclear technology.	4.0	2	7.4	18.5	74.7	Yes
Advancements in closed-loop systems.	4.0	2	7.4	29.6	63.0	No

regeneration of essential resources such as oxygen, water, and food. Nonetheless, the lack of agreement among experts is not due to an underestimate of these systems' potential, but rather to differing opinions on their readiness, cost-effectiveness, and suitability for various mission scenarios. Some consider them indispensable for sustainable, long-duration space habitation, while others remain cautious due to current limitations, high costs, and integration challenges. Conversely, there is a broad consensus on the scalability of these technologies. Given that existing life support systems tend to be mission-specific, there is an acknowledged need for modular, flexible solutions that can be used across different spacecraft and platforms, particularly with the growth of commercial stations and planetary habitats in mind.

Experts agree on the critical role of in-orbit servicing, recycling, and manufacturing. These functions are essential for sustainable space infrastructure because they can extend spacecraft lifespans, reduce reliance on Earth launches, and enable on-site production of parts and materials. In-orbit activities are considered strategic for supporting upcoming human missions while also reducing environmental impacts and operational expenses. As these technologies develop, they are likely to reshape traditional mission designs, moving away from disposable systems toward circular, reusable models. In contrast, international collaboration did not achieve a consensus. This probably stems from uncertainties related to geopolitical tensions and the fragmented nature of global space governance, which remain barriers to effective cooperation and the creation of shared long-term objectives.

4.2.7. Geopolitics and Defence

For each investigated category, experts were asked to indicate the geographic area they believed would most strongly drive technological development in the coming years.

As shown in Table 18, Europe is expected to play a key role in debris mitigation technologies and Earth observation activities. This expectation likely stems from the strong commitment demonstrated by institutions such as the European Space Agency (ESA) and targeted initiatives like ClearSpace-1. These initiatives underscore Europe's focus on orbital sustainability and responsible space operations. Europe has a well-established tradition in Earth observation, particularly in the collection and processing of environmental and civil data. By contrast, the United States is seen as the main leader in access-to-space technologies, spacecraft development, and telecommunications. This perception is supported by the dynamism of the U.S. private sector, particularly companies such as SpaceX and Blue Origin, which have transformed space access through innovations like reusable launch systems and large-scale satellite constellations for global internet access (e.g., Starlink). Additionally, the strong synergy between U.S. public institutions (e.g., NASA and the DoD) and private industry ensures sustained investment, continuity, and scalability across a broad range of space projects. Meanwhile, China is expected to lead the development of LSS and related technologies for exploration, habitat construction, and resource management on other celestial bodies. This prediction is based on China's long-term space strategy, which includes successful robotic lunar missions (e.g., Chang'e), deployment of the Tiangong space station, and increasingly ambitious plans for crewed lunar exploration and beyond (see Table 19).

Regarding investments, both public and private, experts agree on a significant increase over the next 15 years in all areas analyzed, except for LSS and ISRU technologies, for which no clear consensus emerges. This uncertainty could be partially explained by a bias stemming from the underrepresentation of experts from the Asian continent, particularly China, which, as highlighted in previous results, is considered a leader in the technological development of these capabilities.

Similar results emerge for defence and security investments: a general increase is expected, except for the space debris mitigation category, where there is no consensus among experts (see Table 20). Generally, there is agreement that increased investment in defense and security will have a significant impact on the development of space technologies, accelerating their innovation and adoption across various domains, particularly in telecommunications.

5. Conclusion

This study explores expected trends in space sustainability through 2040 and the roles of key stakeholders in shaping them. A three-round Delphi survey involving 63 academic, governmental, and industrial experts uses both open- and closed-ended questions rated on a five-point Likert scale. Consensus was measured through three criteria: response polarization, interquartile range (IQR), and mean values. The first two rounds were conducted consecutively, while the third, held one year later, examined how expert perspectives evolved amid geopolitical changes between 2024 and 2025.

Three essential patterns emerge from the synthesis of results across the thematic domains. First, the dual leadership of space agencies and large private companies is a consistent finding of the study, holding across every technological area examined. Second, expert consensus systematically declined between the second and third survey rounds, most markedly regarding the roles of universities, research centers, and international organizations, reflecting a structural shift driven by the geopolitical changes of 2024–2025. As a consequence, the role of academia in the space industry is being actively eroded by shifting funding priorities. Finally, investment growth is expected across all technological domains, with one notable exception: life support systems and ISRU technologies, where experts did not converge. This divergence reflects both the limited commercial market for deep-space exploration technologies and the uncertainties surrounding international collaboration in this area.

Findings indicate that the global space economy, expected to exceed USD 1 trillion by 2040, will remain both geographically and technologically fragmented. Europe is likely to consolidate its leadership in Earth observation and remote sensing, whereas the United States is expected to maintain dominance in telecommunications and launch technologies. Experts anticipate increasing investment flows, particularly in defense and security, which will stimulate innovation but risk deepening regional and sectoral inequalities.

Sustainability-related technologies will require substantial funding and stronger international collaboration to progress effectively. In particular, advancing sustainability in access-to-space technologies will depend on investments in green propellants, environmentally friendly combustion materials, and reusable launch systems to reduce costs and environmental impact. Regarding debris mitigation, experts agree on the need to improve tracking systems and enhance natural deorbiting

Table 18
Results for the question: Considering your previous answers, which geographical area do you expect to lead technological development in each of the following fields?

Tech.field	U.S.	Europe	China	Japan	Other areas	Not sure	Total
Debris	11.4	65.7	2.9	8.6	0.0	11.4	100.0
Access to space	62.9	2.9	28.6	2.9	0.0	2.9	100.0
Navigation (Remote Sensing)	42.9	25.7	20.0	2.9	0.0	8.6	100.0
Earth Observation	28.6	48.6	11.4	2.9	0.0	8.6	100.0
Telecommunication	60.0	5.7	20.0	0.0	2.9	8.6	100.0
LSSs and ISRU	22.9	11.4	51.4	2.9	0.0	11.4	100.0
Spacecraft	51.4	5.7	25.7	2.9	0.0	14.3	100.0

Table 19
Results for the question: Looking at the global scenario, will public and private investment in the following technological areas decrease or increase in the next 15 years?

Tech.field	mean	Public and Private Investments			Slightly increase or Increase [%]	Consensus
		IQR	Decrease or Slightly decrease [%]	No variation [%]		
Debris	4.0	2	14.3	11.4	74.3	Yes
Access to space	4.6	1	2.9	2.9	94.3	Yes
Navigation (Remote Sensing)	4.1	1	2.9	17.1	80.0	Yes
Earth Observation	4.0	2	5.7	28.6	65.7	Yes
Telecommunication	4.3	1	2.9	11.4	85.7	Yes
LSSs and ISRU	3.8	2	8.6	28.6	62.9	No
Spacecraft	4.0	1	2.9	20.0	77.1	Yes

Table 20
Results for the question: Considering the global scenario, do you expect public and private Defence & Security investments to have an impact on the development of space technology in the next 15 years?

Tech.field	Defence & Security investments					
	mean	IQR	Decrease or Slightly decrease [%]	No variation [%]	Slightly increase or Increase [%]	Consensus
Debris	3.5	3	28.6	20.0	51.4	No
Access to space	4.3	1	8.6	11.4	80.0	Yes
Navigation (Remote Sensing)	4.2	1	0.0	20.0	80.0	Yes
Earth Observation	4.3	1	5.7	14.3	80.0	Yes
Telecommunication	4.5	1	0.0	5.7	94.3	Yes
LSSs and ISRU	3.4	1	22.9	31.4	45.7	No
Spacecraft	4.0	1	8.6	11.4	80.0	Yes

processes. Navigation and Earth observation technologies are expected to be led by large companies and space agencies, whereas telecommunications will be dominated by major private firms. According to most experts, progress toward sustainability will also depend on promoting data democratization and sharing, supported by investment that lowers GEO operational costs and strengthens international cooperation.

Private actors (start-ups, SMEs, and large companies) will play a central role alongside governmental space agencies. Yet, because market incentives primarily drive private investment, robust legal and policy frameworks will be essential to guide technological development toward sustainable practices. Experts highlighted a persistent lack of comprehensive policy and legal mechanisms explicitly supporting space sustainability, with future regulatory trajectories remaining uncertain and divided.

Consistent with previous research on particular aspects of space sustainability [105–107] this study broadens the analytical scope. Previous studies have linked sustainability to social legitimacy, energy infrastructure, or inclusive governance; this research combines these perspectives and shows that by 2040, sustainable space activities will hinge on balancing technological innovation, international governance, and global political-economic factors.

Ultimately, the geopolitical landscape will continue to shape the space domain, influencing cooperation, stakeholder roles, and the global balance of power. Ensuring a sustainable and cooperative future in space requires stronger international governance through updated legal frameworks, transparent policy instruments, and inclusive partnerships that balance public and private interests.

CRediT authorship contribution statement

Federico Caviggioli: Conceptualization, Data curation, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. **Giuseppe Scellato:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **Marianna Valente:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

The following tables (Table 21, Table 22, Table 23, Table 24, Table 25, Table 26, Table 27, and Table 28) report the results from the second round, administered to the expert panel in 2024.

Table 21
Results for Q1: Do "Space Laws and Regulations" encourage sustainable practices, considering environmental, social, and economic factors, today? And in 2040?

	Law and regulation											
	Today						By 2040					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Environmental sustainability	2.6	2	50.0	33.3	16.7	No	3.6	1	18.5	14.8	66.7	Yes
Social sustainability	2.5	2	50.0	33.3	16.7	No	2.6	1	51.9	29.6	18.5	No
Economic Sustainability	2.5	2	50.0	38.9	11.1	No	2.6	2	51.9	22.2	25.9	No

Table 22
Results for Q2: How effectively are "space policies" supporting the sustainability of space activities in terms of the environment, economy, and society in the present day? And in 2040?

	Space Policy											
	Today						By 2040					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Environmental sustainability	2.8	2	37.1	37.1	25.7	No	3.2	1	15.4	11.5	73.1	Yes
Social sustainability	2.5	1	45.7	45.7	8.6	No	2.9	2	61.5	3.8	34.6	No
Economic Sustainability	2.7	1	37.1	40.0	22.9	No	3.1	2	34.6	15.4	50.0	No

Table 23
Results for Q3: Please rate the effectiveness of these initiatives for the sustainable development of "Space Law and Regulations" and "Space Policy" up to 2040.

	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Strengthening of National legislative/regulatory bodies	3.7	2	13.8	31.0	55.2	No
Strengthening of International legislative/regulatory bodies.	4.0	1	13.8	10.3	75.9	Yes
Creation of New International bodies.	3.0	2	31.0	27.6	41.4	No
Introduction of more severe sanctions.	2.9	1	44.8	27.6	27.6	No

Table 24
Results for Q5: Considering the technologies for "debris mitigation," please rate the importance of the following stakeholders in supporting sustainable development.

	Debris mitigation technology											
	Today						By 2040					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Large private companies	3.5	1	15.2	27.3	57.6	No	4.3	1	6.1	12.1	81.8	Yes
SMEs and startups	3.3	1	18.2	30.3	51.5	No	4.1	1	13.3	6.7	80.0	Yes
Space agencies, national and intergovernmental bodies	4.3	1	9.1	9.1	81.8	Yes	4.6	1	3.0	3.0	93.9	Yes
Universities and public research centers	3.2	2	27.3	36.4	36.4	No	4.0	1	13.3	10.0	76.7	Yes
Other international organizations	3.5	2	18.2	36.4	45.5	No	3.9	2	12.1	15.2	72.7	Yes

Table 25
Results for Q8: Considering "Access to Space" technologies, please rate the importance of the following stakeholders in supporting sustainable development.

	Access to space technology											
	Today						By 2040					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Large private companies	3.9	2	12.1	15.2	72.7	Yes	4.5	1	3.0	6.1	90.9	Yes
SMEs and startups	3.2	2	30.3	30.3	39.4	No	4.0	2	10.7	14.3	75.0	Yes
Space agencies, national and intergovernmental bodies	4.0	2	6.1	21.2	72.7	Yes	4.2	1	3.0	21.2	75.8	Yes
Universities and public research centers	2.9	2	42.4	24.2	33.3	No	3.6	3	25.0	17.9	57.1	No
Other international organizations	2.7	1	45.5	30.3	24.2	No	3.4	3	32.1	14.3	53.6	No

Table 26
Results for Q10: Considering technological advancements in "Spacecraft," please rate the importance of the following stakeholders in supporting sustainable development.

	Spacecraft Design											
	Today						By 2040					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Large private companies	4.2	1	6.9	13.8	79.3	Yes	4.5	1	6.9	3.4	89.7	Yes
SMEs and startups	3.7	2	17.2	24.1	58.6	No	4.1	1	6.9	10.3	82.8	Yes
Space agencies, national and intergovernmental bodies	3.9	2	6.9	34.5	58.6	No	4.4	1	11.1	3.7	85.2	Yes
Universities and public research centers	3.4	1	20.7	31.0	48.3	No	4.0	2	14.8	14.8	70.4	Yes
Other international organizations	2.3	2	55.2	27.6	17.2	No	2.5	2	59.3	11.1	29.6	No

Table 27
Results for Q 13: Considering "Remote sensing and Data handling" activities, please rate the importance of the following stakeholders in supporting sustainable development.

	Remote sensing and data handling activities											
	Today						By 2040					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Large private companies	3.6	1	13.8	31.0	55.2	Yes	4.1	1	3.4	17.2	79.3	Yes
SMEs and startups	3.7	1	10.3	27.6	62.1	Yes	4.1	1	3.4	17.2	79.3	Yes
Space agencies, national and intergovernmental bodies	4.1	2	6.9	20.7	72.4	Yes	4.1	2	3.4	24.1	72.4	Yes
Universities and public research centers	3.4	1	13.8	41.4	44.8	No	3.7	1	13.8	17.2	69.0	Yes
Other international organizations	2.8	2	41.4	31.0	27.6	No	3.5	3	33.3	14.8	51.9	No

Table 28
Results for Q15: Considering technologies for "Life support system and ISRU," please rate the importance of the following stakeholders in supporting sustainable development.

	LSSs and habitat design											
	Today						By 2040					
	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus	mean	IQR	Not at all or Slightly [%]	Moderately [%]	Very or Extremely [%]	Consensus
Large private companies	3.3	1	23.3	30.0	46.7	No	4.2	1	6.7	13.3	80.0	Yes
SMEs and startups	3.3	2	33.3	20.0	46.7	No	4.2	2	7.4	18.5	74.1	Yes
Space agencies, national and intergovernmental bodies	4.0	2	10.0	16.7	73.3	Yes	4.0	2	6.7	20.0	73.3	Yes
Universities and public research centers	3.7	3	26.7	6.7	66.7	Yes	3.8	2	16.7	13.3	70.0	Yes
Other international organizations	2.6	3	50.0	23.3	26.7	No	3.2	2	33.3	22.2	44.4	No

Data availability

Data will be made available on request.

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