

Pioneering the Future: Space Technologies Poised to Revolutionize Exploration and Economy by 2035

INSIGHT REPORT

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Foreword



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Space has always made us look upward, but its importance today is no longer only about exploration. It is becoming one of the arenas where the future economy will be shaped. The technologies being developed for space are changing how we think about connectivity, security, sustainability, scientific discovery, and industrial growth on Earth. This makes space not only a frontier but a testbed for the capabilities that will define the next decade.

The question we must ask is not simply what is possible in space. The more urgent question is what will become useful, scalable, and economically meaningful. Many technologies can inspire excitement, but only some will mature into the systems that change how missions are designed, how infrastructure is built, and how value is created. Understanding that difference is essential if we want to move beyond ambition and toward real impact.

This is why the Centre for Space Futures launched the Space Technologies Flagship Initiative. We want to examine the technologies most likely to shape the space economy by 2035 with clarity, discipline, and a practical view of what it takes for innovation to mature. The goal is not to produce another report about the promise of space; it is to identify where technological momentum is built, where barriers remain, and where coordinated action can accelerate progress.

This report is intentionally detailed because the future of space cannot be understood through headlines alone. Behind every breakthrough is a longer story of engineering constraints, market uncertainty, policy choices, investment risk, and operational reality. Some technologies are already moving closer to commercial adoption. Others remain at an earlier stage of development, with enormous potential but important challenges ahead. Both matter, but they require different types of support and different expectations.

That distinction is important because the space sector does not need more hype. It needs sharper judgment. Governments need to know where to focus capability development. Investors need to understand where promise is matched by credible pathways to market. Companies need to see where demand may emerge. Researchers and entrepreneurs

need to understand which problems are worth solving now, and which ones will define the next wave of opportunity.

For emerging space nations, this moment is especially significant. The future space economy will not be shaped only by those who led in the past. It will also be shaped by those who can identify strategic entry points, build the right partnerships, and invest in capabilities that create long-term relevance. Space is changing quickly, and the states and organizations that understand these shifts will be better positioned to participate with purpose rather than follow from the sidelines.

This report is more than a technology scan. It is an invitation to think strategically about the future we are building. I hope it challenges assumptions, sharpens priorities, and gives readers a clearer view of where the next era of space is heading. Most importantly, I hope it encourages action, because the future of space will not be defined by those who observe it. It will be defined by those who build it.



Table of Acronyms

Acronym	Definition
5G	Fifth-generation mobile network
6G	Sixth-generation mobile network
AC	Advisory Committee
ADR	Active Debris Removal
AEPS	Advanced Electric Propulsion System
AI	Artificial Intelligence
AP&SPS	Advanced Propulsion and Space Power Systems
ASIC	Application-Specific Integrated Circuit
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CLPS	Commercial Lunar Payload Services
CSF	Centre for Space Futures
EBITDA	Earnings Before Interest, Taxes, Depreciation, and Amortization
EO	Earth Observation
EP	Electric Propulsion
ESA	European Space Agency
EU	European Union
FDIR	Fault Detection, Isolation, and Recovery
FPGA	Field-Programmable Gate Array
GEO	Geostationary Earth Orbit
GNC	Guidance, Navigation, and Control
GNSS	Global Navigation Satellite System
GNP	Gross National Product
ILRS	International Lunar Research Station
IoT	Internet of Things
ISAM	In-Space Servicing, Assembly, and Manufacturing
ISRU	In-Situ Resource Utilization
ISR	Intelligence, Surveillance, and Reconnaissance

Acronym	Definition
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
LEO	Low Earth Orbit
LUPEX	Lunar Polar Exploration Mission
MTCR	Missile Technology Control Regime
MEO	Medium Earth Orbit
Mkt-RL	Market Readiness Level
MRL	Manufacturing Readiness Level
NASA	National Aeronautics and Space Administration
NTN	Non-Terrestrial Network
OSAM	On-Orbit Servicing, Assembly, and Manufacturing
PE	Private Equity
PNT	Positioning, Navigation, and Timing
R&D	Research and Development
RDRE	Rotating Detonation Rocket Engine
RF	Radio Frequency
RISC	Reduced Instruction Set Computer
ROI	Return on Investment
RPOD	Rendezvous, Proximity Operations, and Docking
RPO	Rendezvous and Proximity Operations
SATCOM	Satellite Communications
SC&ODI	Space Communications and On-Orbit Data Infrastructure
SDA	Software-Defined Architecture
SNP&P	Space Nuclear Power and Propulsion
SpaDeX	Space Docking Experiment
SSA	Space Situational Awareness
SST	Space Surveillance and Tracking
STM	Space Traffic Management
TRL	Technology Readiness Level
UNCTAD	United Nations Conference on Trade and Development
VC	Venture Capital

Executive Summary

Space technologies are entering a decisive decade in which technological ambition must translate into market adoption, investment confidence, and strategic capability. As the global space economy is projected to expand significantly by 2035, emerging space technologies will play a central role in shaping future exploration, national capabilities, commercial competitiveness, and cross-sector innovation. This report, developed by the Centre for Space Futures through expert consultations, survey analysis, workshop discussions, and Advisory Committee validation, identifies five priority technology areas with the potential to transform the space sector over the next decade.

The five technology clusters assessed are: Artificial Intelligence (AI), Autonomy, and Robotics; In-Space Servicing, Assembly, and Manufacturing (ISAM) and On-Orbit Servicing, Assembly, and Manufacturing (OSAM); Advanced Propulsion and Space Power Systems (AP&SPS); In-Situ Resource Utilization (ISRU) and Space Resources; and Space Communications and On-Orbit Data Infrastructure (SC&ODI). Together, these technology clusters represent the operating, mobility, infrastructure, resource, and data layers of the future global space economy. They are not isolated domains: AI enables autonomy and mission optimization; propulsion and power systems enable mobility and endurance; ISAM and OSAM enable serviceable and circular space infrastructure; ISRU enables sustained lunar and deep-space operations; and space communications provide the digital backbone for real-time, universal, and secure space activity.

The assessment shows that maturity is uneven. Space communications, AI-enabled analytics, electric propulsion, and selected critical subsystems are closer to commercial adoption. ISRU, large-scale in-space manufacturing, orbital data centers, Space

Nuclear Power and Propulsion (SNP&P) technologies, and autonomous servicing remain dependent on demonstrations, standards, and anchor demand. Across all five clusters, the recurring barriers are: limited flight heritage and testing infrastructure, significant upfront investment requirements, long return horizons, regulatory uncertainty, fragmented standards, multi-application sensitivities, and weak early demand signals.

The report also finds that investor confidence increases when technologies demonstrate clear customer demand, validated milestones, public anchor procurement, strong technical teams, and credible routes to scale. Conversely, private investor hesitation is strongest where business models remain unclear, timelines exceed normal venture horizons, and regulatory or liability frameworks remain underdeveloped.

The findings indicate that the strategic way forward requires coordinated action across stakeholders. Such action would include system-level demonstrations, shared testbeds, standardized interfaces, clearer authorization pathways, public-private co-investment, cross-sector partnerships, and anchor-customer procurement. By connecting innovators, investors, and institutional demand, this initiative aims to help promising technologies cross the “valley of death” and become deployable capabilities for a more resilient and sustainable global space economy.

01

Introduction

Systemic gaps between technological progress, investment alignment, and market access put emerging space technologies at risk.

Since the 1980s, innovation in the space sector has been monumental. Over the past decade, the rise of commercial actors drove a structural shift often referred to as the “NewSpace”¹ movement. This shift has lowered barriers to entry, enabling a broader range of companies to develop and commercialize space technologies with reduced reliance on government funding.² As a result, the pipeline of emerging space technologies has expanded significantly, introducing new capabilities and accelerating innovation across the sector. Despite increased participation and innovation, the transition from development to operational deployment remains constrained.

As part of the Centre for Space Futures’ (CSF) Space Technologies Flagship Initiative, this report identifies the emerging space technologies most likely to shape the next decade of the global space economy. For this assessment, emerging space technologies refer to the priority technologies identified through CSF’s survey and categorized into five technology clusters. Each cluster is assessed to understand the constraints these technologies face as they move from development to deployment.

Limitations include inconsistent access to funding, specialized technical expertise, skilled talent, testing infrastructure, and enabling regulatory environments, all of which hinder the development of emerging space technologies. Technologies failing to transition from validation to commercial deployment enter what is commonly referred to as the “valley of death” (Figure 1). At this stage, promising solutions face additional constraints³ in securing funding, gaining

market access, or acquiring the institutional support required to scale. This challenge reflects a structural misalignment between market demand, technological advancement, and investment readiness.

The progression of emerging space technologies depends on both technical maturity and the existence of functioning markets that support economic viability. Weak visibility and fragmented investment signals make it difficult to align technology development with market demand effectively. In the space sector, this challenge is shaped by the central role of government strategies in directing investment, creating demand, and shaping market conditions.

The global space economy continues to expand, serving as a foundational layer for terrestrial applications such as communications, navigation, climate monitoring, and protective systems. With the global space economy projected to reach \$1.8 trillion by 2035,⁴ the successful advancement and commercialization of emerging space technologies would contribute to its sustainable growth. This effort requires continued innovation that translates into scalable, investable opportunities. Realizing this potential requires greater investor confidence and clearer pathways to market adoption.

As the volume of innovation increases, so does the complexity of identifying the technologies that could achieve market traction. Transitioning solutions from concept to deployment requires targeted investment, stronger market alignment, and greater visibility across the ecosystem. In parallel,

investors require insights to assess opportunities, manage risk, and allocate capital effectively.

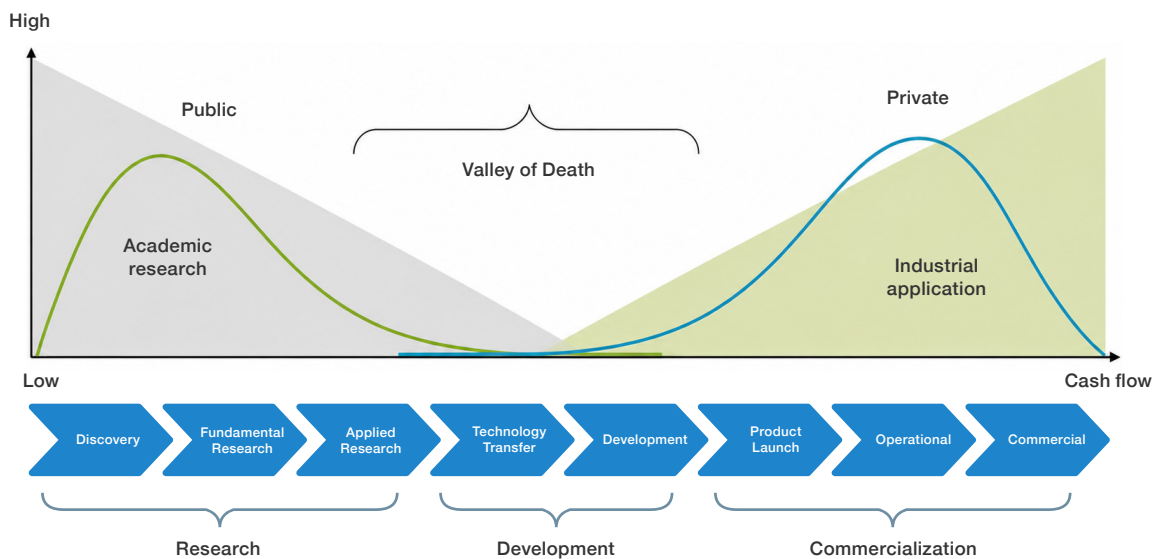


Figure 1: Illustration of the “Valley of Death”

In the NewSpace era, commercialization unlocked unprecedented innovation; without appropriate support, many breakthrough technologies stall in the “valley of death” before reaching the market.

This report is the first edition of CSF’s Space Technologies Flagship Initiative. It identifies the initial set of the top five high-potential technologies. The second edition will complete the full set of the top 10 emerging space technologies. The phased approach allows for iterative validation within the broader ecosystem, as technology trajectories and market signals evolve in parallel.

The initiative is structured around three core outputs (Figure 2): Phase I and Phase II reports, concise factsheets for the top 10 technologies, and a marketplace platform that makes the insights accessible and helps connect technology developers with investors and industry stakeholders. The reports provide in-depth assessments of key technology domains, while the factsheets offer snapshots of Technology Readiness Levels (TRLs), Manufacturing Readiness Levels (MRLs), and Market Readiness Levels (Mkt-RLs). Together, these outputs aim to educate the market, enhance investor

exposure, increase investment participation, and improve matchmaking efficiency.

This initiative aims to increase the visibility of high-potential emerging space technologies, strengthen alignment between innovators, investors, and industry, and catalyze investment flows. It also seeks to accelerate commercialization and support the development of a more mature and accessible space economy. Together, these efforts will help unlock the future of growth in the space economy, translating technological potential into economic and strategic value.

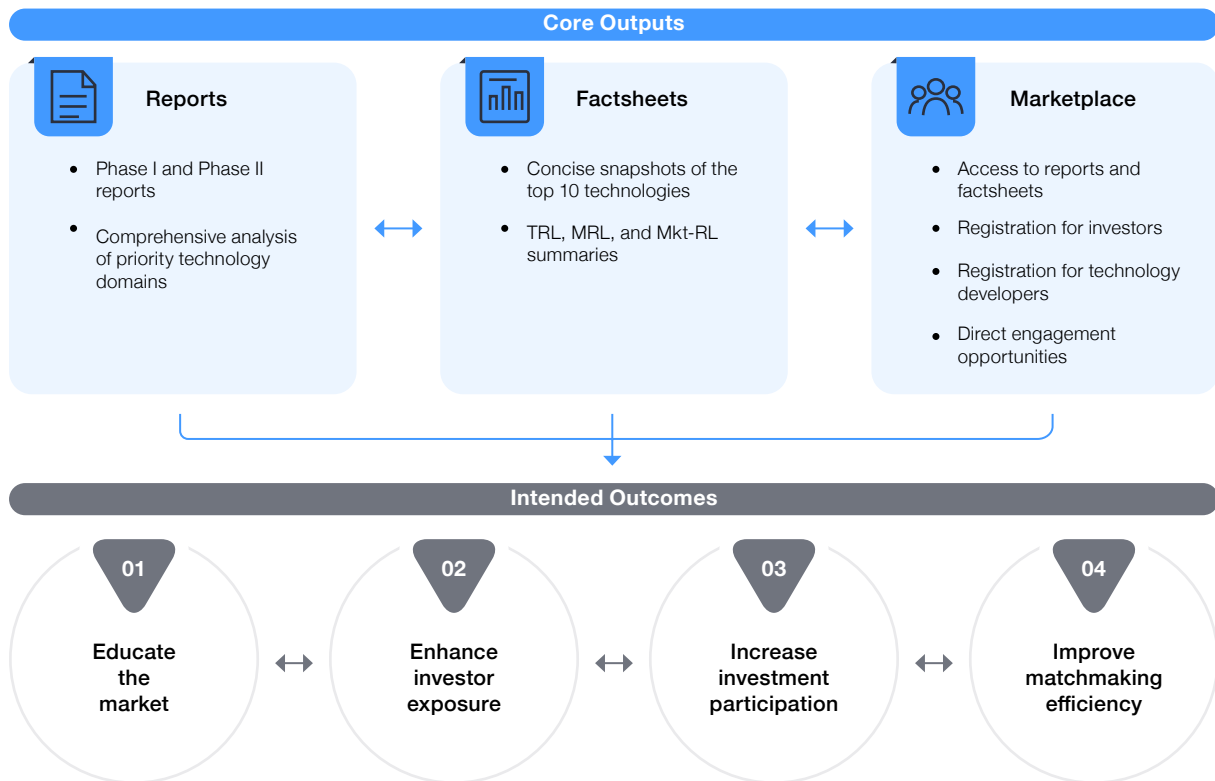


Figure 2: Outputs and Outcomes of CSF's Space Technologies Flagship Initiative

1.1

Partners and Expert Ecosystem

The initiative is supported by a coordinated working group comprising the CSF leadership team, institutional partners, and an Advisory Committee (AC) of external experts. As illustrated in Figure 3, the AC brings together experts representing a broad range of technical, economic, regulatory, and geographic perspectives. Regular strategic guidance, technical validation, and stakeholder engagement ensure a robust, multidisciplinary foundation for the report's work.

CSF leads the initiative, advocates for community voices, chairs the AC through its Managing Director, and oversees secretariat duties. It also ensures coordination, methodological consistency, and alignment with the broader objectives of the initiative. CSF's key responsibilities are to:

- Lead and coordinate the AC

- Manage the assessment process and workflow
- Integrate expert recommendations into the final publication
- Lead and implement communication and dissemination strategies

The AC brings together a diverse group of experts representing a broad range of technical, economic, regulatory, and geographic perspectives. This multidisciplinary composition reinforces the credibility and depth of the assessment.

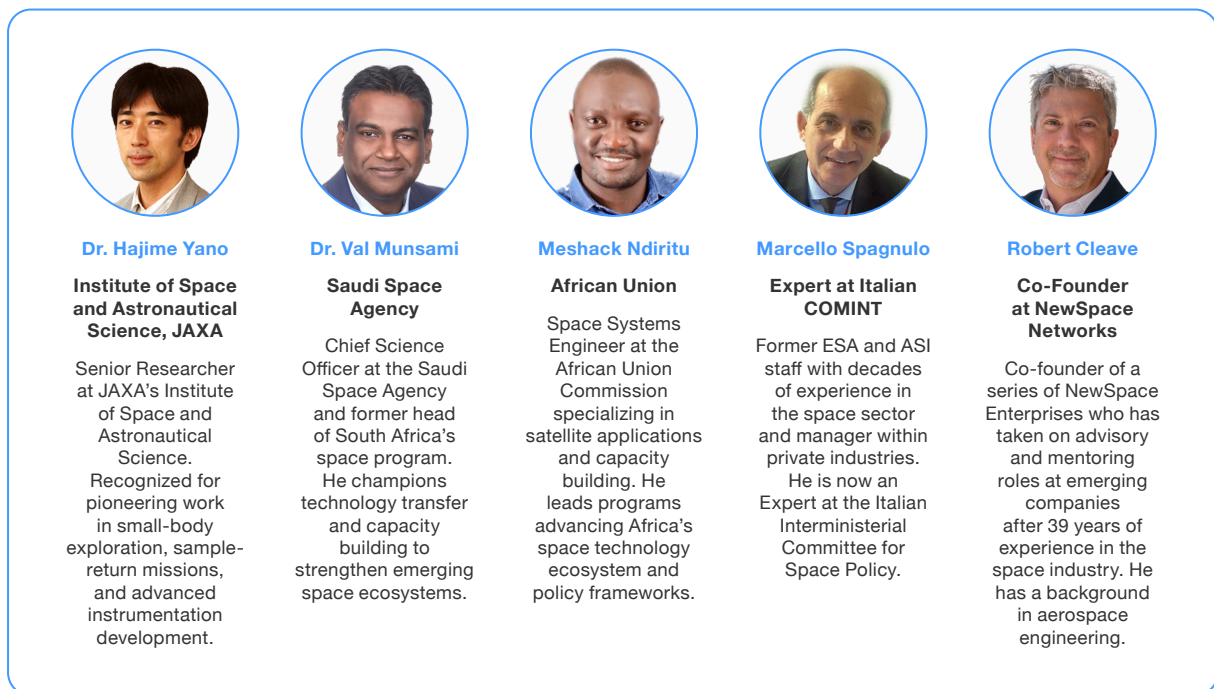


Figure 3: Advisory Committee Members

The AC contributes to the initiative by performing the following functions:

- Guide the selection and assessment of candidate technologies included in the report
- Validate the evaluation criteria to ensure they reflect technological promise, cross-sector relevance, and emerging market needs
- Identify key technical, regulatory, and financial challenges, while highlighting pathways for technology maturation and commercialization
- Provide insights into cross-cutting capabilities and terrestrial applications
- Review and endorse the report's findings, analysis, and recommendations
- Support outreach and dissemination efforts to maximize the initiative's impact

CSF collaborates with strategic partners to expand the initiative's reach and leverage international expertise. These partnerships enhance access to advanced knowledge, analytical methodologies, and global networks.

The partner institutions are:

- **BryceTech:**⁵ U.S.-based analytics and engineering firm specializing in space-sector analytics, market intelligence, strategic advisory, and data-driven insights
- **King Abdullah University of Science and Technology (KAUST):**⁶ Saudi Arabia-based graduate research university specializing in science, technology, engineering, and innovation
- **The European House of Ambrosetti (TEHA):**⁷ Italy-based strategic consultancy and think tank specializing in strategic studies, high-level research, economic analysis, and public-private dialogue

Table 1 summarizes the key actors, roles, and contributions supporting the initiative.

Table 1: Key Roles and Contributions Supporting the Initiative

Role	Stakeholder	Contribution
Governance & Coordination	Centre for Space Futures	Strategic leadership, methodology, process coordination, and report delivery
Expert Advisory	Advisory Committee	Technical validation, assessment oversight, and expert insight
Strategic Partnerships	• BryceTech • KAUST • TEHA	Knowledge expansion, analytical support, and access to international expertise and networks

This structure ensures a balanced approach that integrates technical expertise, sector intelligence, and institutional credibility to guide informed decision-making across the space technology landscape.

1.2

Methodology and Approach

A phased, expert-led, and ecosystem-driven approach that bridges innovation, investment, and market adoption to advance the sustainable growth of the global space economy.

CSF's Space Technologies Flagship Initiative adopts a staged methodology designed to identify, validate, and activate the emerging space technologies most likely to shape the next decade of the space economy. The process begins with community consultations to surface high-potential technologies, followed by expert validation from the AC to refine the selection and strengthen the assessment. These validated technologies then form the basis for matchmaking between technology developers, companies, and investors through a dedicated web-based marketplace. Table 2 summarizes the initiative's phased framework, including the main activities, methodology, and expected outputs for each phase. This consultative model builds a curated portfolio of the top 10 priority technologies and translates

the initiative's findings into pathways for ecosystem engagement, market development, and investment activation.

Phase I identifies the first set of the top five priority emerging space technologies. The identification process is based on an expert survey that reveals the most frequently prioritized technologies, complemented by one-on-one consultations, a dedicated workshop, and feedback from the AC. The output of Phase I is this report, which presents deep dives and factsheets on the top five emerging space technologies.

Phase II extends this work through an online consultation to identify the additional top five emerging space technologies. Following the same approach as Phase I, the second report completes the full set of the top 10 emerging space technologies and their corresponding factsheets.

Phase III is the activation phase, in which the identified top 10 emerging space technologies are used to develop an online platform. The platform will host the 10 factsheets and open registration for companies, technology developers, and investors. This phase aims to transform the list of priority emerging space technologies into a living marketplace that connects solution providers, innovators, and investors.

The final phase focuses on long-term evaluation and collaboration. Following

the platform launch, CSF will continue to monitor progress, gather feedback from the community and the AC, and enable further cooperation. Success in this phase is assessed through platform activity, stakeholder participation, quality of investor and technology-developer engagement, and evidence of emerging

collaboration opportunities. Through this phased methodology, technology identification becomes the foundation for broader ecosystem engagement, market development, and sustained collaboration across the space sector.

Table 2: Phased Framework of the Space Technology Flagship Initiative

Process	Phase I: Top Five Technologies	Phase II: Additional Top Five Technologies	Phase III: Marketplace	Evaluation & Collaboration
Activity	Identify the initial top five priority emerging space technologies	Identify the additional top five priority emerging space technologies	Establish an online platform for the top 10 emerging space technologies and open registration for companies, technology developers, and investors	Follow up and review progress to support continued collaboration
Methodology	CSF survey; one-on-one consultations; workshop; AC feedback	Analysis of online consultation results; AC feedback; technical partner consultations	AC feedback on the registration form and applications	Partner support for promotion and dissemination
Outcome	This first report presenting the top five technologies and accompanying factsheets	A second report presenting the additional top five technologies and accompanying factsheets	An online platform for registered companies, technology developers, and investors	Evidence of stakeholder engagement and emerging collaboration opportunities

1.3

Strategic Context

Space is becoming a critical layer of the global economy, underpinning infrastructure, national capability, and future competitiveness.

Space-based capabilities underpin critical infrastructure, including communications, navigation, financial systems, climate monitoring, and government assets. As reliance on these systems increases, space is becoming more tightly integrated into the function of the global economy and strategic national infrastructures. The global space economy is projected to grow from \$630 billion in 2023 to \$1.8 trillion by 2035,⁸ underscoring its expanding influence. This shift elevates space from a specialized domain to a foundational layer of modern economic and strategic activity.

At the same time, the structure of the space ecosystem is being reshaped by geopolitical competition, commercialization, and rapid technological change.⁹ International cooperation, historically driven by scientific objectives, is increasingly influenced by strategic and government priorities. Access to supply chains, orbital infrastructure, and advanced capabilities is becoming more closely tied to alliances, national interests, and control over critical technologies.¹⁰

In parallel, states are prioritizing technological resilience, responsiveness, and greater independence in space capabilities.¹¹ This shift is driven by increasing congestion in orbit, rising debris risks,¹² and intensifying competition over limited orbital and spectral resources. As a result, space is no longer viewed as an open domain but as a contested, capacity-constrained environment¹³ requiring active management and strategic positioning.

These dynamics are creating a more fragmented and uneven global landscape. States with advanced capabilities are shaping

norms, controlling access, and capturing a disproportionate share of economic and strategic value. At the same time, broader participation through commercial actors is lowering barriers to entry, while introducing new dependencies across supply chains, materials, and critical subsystems.

Competition in space is increasingly defined by access, capabilities, and influence, each shaped by strategic priorities.

Emerging space technologies sit at the center of this transition. Beyond enabling scientific discovery and exploration, they define the ability of states and industries to compete, collaborate, and operate effectively in this evolving environment. Their development and deployment influence not only economic growth but also technological autonomy, resilience, and long-term strategic advantage.¹⁴

The increasing commercialization of the sector is accelerating innovation, driving faster development cycles and more scalable solutions. However, this shift also places greater pressure on governance frameworks to ensure sustainability, interoperability, and equitable access. Meanwhile, innovation in space remains capital-intensive, high-risk, and dependent on long development timelines, requiring coordinated support across public and private actors.

In this context, emerging space technologies are not only drivers of growth but also enablers of strategic positioning in a rapidly evolving global system. Their relevance lies in their ability to support exploration, strengthen domestic technological capabilities, enable applications across multiple domains, and unlock new economic opportunities across multiple sectors. As the space economy continues to mature, the ability to identify, support, and scale these technologies will increasingly define competitive advantage.

The following table presents the criteria and assessment elements used to define the strategic value of each emerging technological area considered under this initiative.

Table 3: Strategic Value Assessment Criteria for Emerging Space Technologies

Criterion	Description	Assessment Element	Example
Government strategies	Enhances deterrence, situational awareness, and protection of national assets and stakes	Intelligence, Surveillance, and Reconnaissance (ISR); warnings; secure connectivity; readiness for counterspace threats; detection and attribution	Geostationary Equatorial Orbit (GEO) constellations for secure communications and warnings; Medium Earth Orbit (MEO) constellations for Positioning, Navigation, and Timing (PNT); Low Earth Orbit (LEO) for secure communication and ISR
Economic value and spillover impact ¹⁵	Contributes to economic growth through direct and indirect benefits	Upstream and downstream market growth; investor attractiveness; productivity gains; industrial competitiveness	Earth Observation (EO) analytics for agriculture, logistics, climate risk, and infrastructure monitoring
Self-sufficiency and supply-chain resilience ¹⁶	Reduces dependence on foreign powers and preserves freedom of action	Control of data, components, manufacturing, deployment access, ground segment, and critical services	Domestic satellite communications (satcom) constellations; data platforms; launch capability
Technological leadership and innovation capacity ¹⁷	Strengthens technological leadership, innovation capacity, and competitive advantage	R&D pace; multi-application relevance; resilient architectures; AI, software, and data capability	Reusable launch vehicles; software-defined payloads; national AI-for-space testbeds
Diplomatic leverage and international influence	Expands influence and partnership options	Setting standards; shared services; science diplomacy; ability to attract partners	EO data provision for disaster response and climate monitoring; Artemis program and the International Lunar Research Station (ILRS)
Critical infrastructure and societal value	Supports essential civilian services and responsiveness	PNT; communications; EO; emergency response; infrastructure dependency	Global Navigation Satellite System (GNSS)/PNT for finance, energy, transport, and emergency services
Talent and institutional capacity	Builds the human and organizational base required to operate, regulate, and scale technologies	Systems engineering, AI/data science, cybersecurity, RF/spectrum, space law, procurement, and mission operations	National training programs, mission operations academies, and university-industry laboratories

02

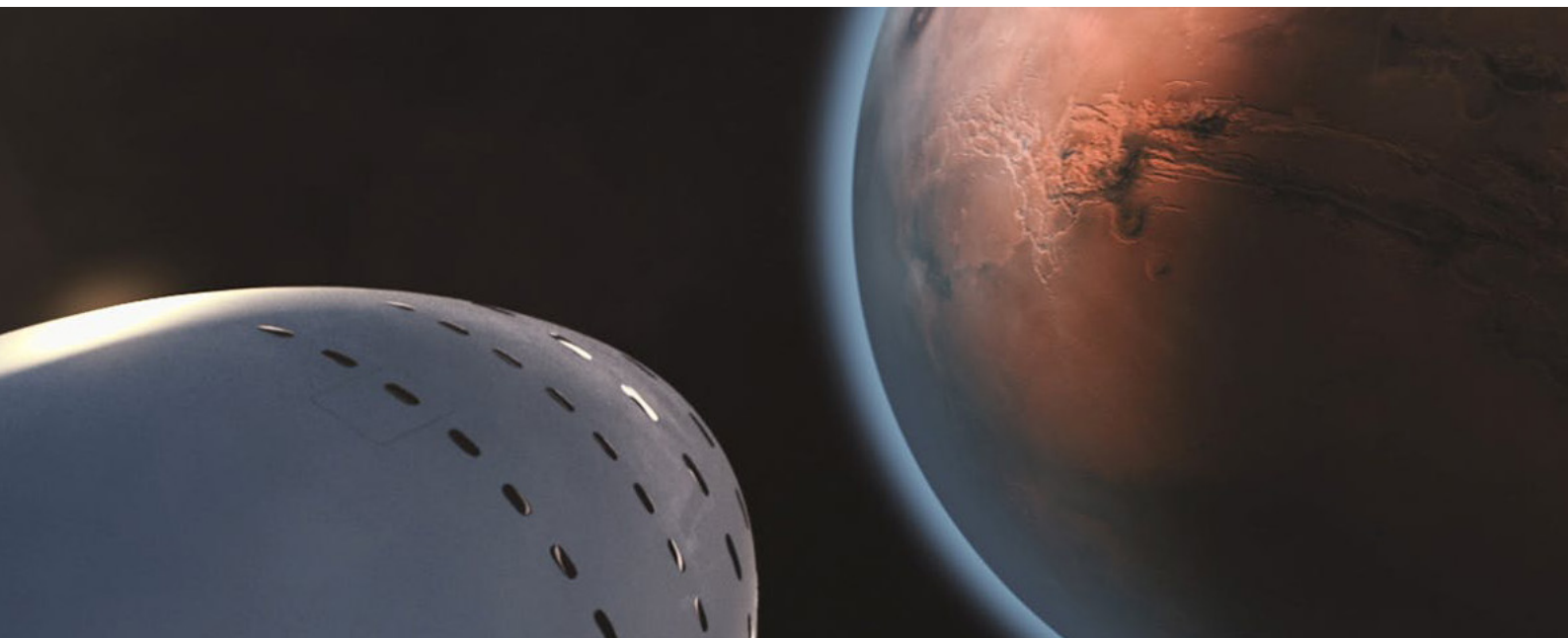
Technology Deep Dives

This section contains focused assessments of the first five emerging space technologies identified through a survey, complemented by one-on-one consultations with space experts, a dedicated workshop, and feedback from the AC. Each deep dive begins by defining the technology cluster and mapping its core capabilities and applications. This is followed by a multifaceted assessment of the maturity of each technological capability on a 1-to-5 scale derived from the CSF survey results.^[a]

To provide deeper context, these scores are mapped against a standardized 1-to-9 readiness framework across three dimensions: Technological Readiness Level (TRL), Manufacturing Readiness Level (MRL), and a bespoke Market Readiness Level (Mkt-RL) developed for this assessment. Each deep dive then presents a qualitative analysis of the technical and operational

barriers to full maturity, complemented by an evaluation of overall market potential and strategic relevance. Cross-cutting applications are also examined to highlight the spillover benefits and opportunities these technologies unlock beyond the traditional space ecosystem.

Finally, the assessments outline estimated timelines for technology maturity, developed in coordination with the AC, and propose concrete measures to accelerate progress. Ultimately, this approach offers decision-makers a comprehensive view of each cluster's current development stage, its future trajectory, and the strategic interventions required to scale their impact.



^[a] The AI, Autonomy, and Robotics cluster is excluded from the 1-to-5 maturity assessment due to the rapid, asymmetric development of its underlying technologies. Instead, the 1-to-9 readiness framework is applied to individual sub-capabilities. This approach avoids the oversimplification of an aggregated cluster-level score, ensuring the granular visibility required for effective strategic decision-making.

2.1

Artificial Intelligence, Autonomy & Robotics

Artificial Intelligence, Autonomy, and Robotics are becoming the operating layer of the next space economy. Their value lies in accelerating decision-making and operational response times, while enhancing safety, scalability, and system resilience.

2.1.1

Definition

Artificial intelligence (AI), autonomy, and robotics are increasingly integrated across the entire space value chain, from design and manufacturing to operations and end-of-life. In this section, AI refers to computational techniques that support perception, prediction, reasoning, planning, language-based knowledge retrieval, and decision support. Autonomy refers to the ability of a spacecraft, payload, ground segment, or robotic system to perform selected functions with reduced real-time human intervention. Robotics refers to physical systems that sense, move, manipulate, inspect, assemble, service, or support operations in space.

The strategic relevance of these technologies lies in augmenting mission assurance and human decision-making while preserving human accountability. Their value is reflected in reduced operational workload, shorter decision cycles, and increased resilience in environments where communication is delayed, intermittent, or unavailable. These capabilities enable missions that would be impractical or impossible under continuous human-in-the-loop control.

This is particularly critical for large-scale

constellations, deep-space missions, ISAM and OSAM, planetary surface operations, and space situational awareness (SSA). As mission complexity increases, the ability to distribute intelligence across systems becomes a core operational requirement. Thus, AI, Autonomy, and Robotics act as force multipliers across both infrastructure and mission execution.¹⁸

Functions of AI-enabled capabilities:

- **Machine learning:** detecting patterns in data and improving classification, prediction, or optimization performance over time.
- **Reasoning, planning, and optimization:** supporting trade-offs, sequencing, route planning, resource allocation, and decision support under constraints.
- **Computer vision and perception:** extracting features from imagery, lidar, radar, telemetry, and other sensor streams to support SSA.
- **Natural language processing and knowledge systems:** retrieving standards, mission heritage, lessons learned, and engineering knowledge from large document or data repositories.
- **Robotic control and manipulation:** translating perception and planning into safe physical action, including navigation,

inspection, rendezvous, docking, maintenance, assembly, and sample handling.

Applications of AI, Autonomy, and Robotics across mission phases:

AI-enabled capabilities support each phase of a space mission, with varying degrees of autonomy depending on mission criticality. In early phases, AI is primarily used for decision support, design optimization, and engineering intelligence. During operations, it enables anomaly detection, onboard data triage, autonomous navigation, and supervised decision-making. In disposal and end-of-life phases, AI can support passivation planning, de-orbit strategy, re-

entry analysis, and post-mission knowledge capture. The degree of autonomy is calibrated to mission criticality, system reliability, operational constraints, and risk tolerance. This progression reflects a shift from assistive to increasingly autonomous roles across the mission lifecycle.

Table 4 maps AI-enabled capabilities across the full mission lifecycle, from mission analysis to disposal. It illustrates how AI functions evolve from decision-support tools in the early phases to increasingly operational and autonomous capabilities throughout mission execution.

Table 4: AI-enabled Capabilities Across the Space Mission Lifecycle

Capability Layer	AI-enabled Capability	Phase 0: Mission Analysis	Phase A: Feasibility	Phase B: Preliminary Definition	Phase C: Detailed Definition	Phase D: Qualification, Verification & Production	Phase E: Operations & Utilization	Phase F: Disposal
Design and Engineering	Concept Generation & Requirements	Mission concepts and use-case framing	Feasibility checks and constraint mapping	Requirements allocation	Requirements traceability	Compliance checks against standards	Requirements update from operations	End-of-life feedback into future missions
	Trade-Off Analysis & Optimization	Architecture trades	Options assessment	Mass, power, and performance budgets	Parameter tuning and sensitivity analysis	Test and production optimization	Mission replanning and resource optimization	Disposal option optimization
	Engineering Knowledge & Support	Heritage data review	System benchmarking	Design review support	Standards and lessons-learned retrieval	Root-cause and non-conformance support	Procedure support and operator decision aids	Lessons learned capture
	Simulation & Digital Twins	Scenario modelling	Performance simulation	Preliminary digital-twin models	Detailed modeling and virtual integration	Virtual testing and model-based V&V	Health and performance prediction	Re-entry and de-orbit simulation
	Verification & Testing Support	Critical test drivers	V&V concept and evidence plan	Test planning	Test case refinement	Test automation and anomaly detection	In-flight performance checks	Disposal verification

Capability Layer	AI-enabled Capability	Phase 0: Mission Analysis	Phase A: Feasibility	Phase B: Preliminary Definition	Phase C: Detailed Definition	Phase D: Qualification, Verification & Production	Phase E: Operations & Utilization	Phase F: Disposal
Operations	Health Monitoring & Predictive Maintenance (including FDIR)	Health indicators and criticality logic	Monitoring feasibility	Telemetry and Fault Detection, Isolation, and Recovery (FDIR) architecture	Diagnostic integration	Model training and validation	Anomaly detection and prognostics	End-of-life monitoring
	Data Processing & Exploitation	Value cases	Analytics feasibility	Processing architecture	Pipeline integration	Analytics validation	Data product generation and prioritization	Archive exploitation
	Space Safety, SSA & Sustainability	Risk context and operational constraints	Mitigation feasibility	Safety-by-design requirements	Resilience and cyber integration	Compliance verification	Conjunction assessment and avoidance support	Debris mitigation verification
Autonomy Systems	Autonomy & Robotics	Autonomy needs and mission value	Functional feasibility and risk envelope	Autonomy architecture and interfaces	Function integration and safety cases	Robustness and fault-injection testing	Autonomous or supervised control, navigation, and robotic tasks	Autonomous or supervised disposal support
	Manufacturing & Quality Assurance	Manufacturing needs and mission value	Production feasibility	Design-for-manufacture inputs	Production preparation and QA plans	Inspection and defect detection	Spare, maintenance, and configuration planning	Material and asset disposition assessment

2.1.2

Maturity Level

The maturity of AI, Autonomy, and Robotics in space applications differs significantly between ground-based capabilities and in-space, mission-critical systems. Ground-based analytics, digital twins, and mission-support software are relatively mature, although sustained operations at scale in real mission environments remain limited. In contrast, safety-critical onboard autonomy, autonomous rendezvous and proximity operations (RPO), distributed swarm systems, and space-rated robotic manipulation remain constrained.

These constraints are driven by several factors, including limited availability of representative test data, stringent mission-assurance requirements, challenges in validation and qualification, and issues related to acceptance and trust. Hardware limitations, particularly the availability of radiation-tolerant and space-qualified computing, further restrict deployment in operational environments. Together, these factors slow the transition from demonstration to reliable, mission-critical use.

Table 5 provides an indicative assessment of maturity using TRL, MRL and Mkt-RL. These values should be interpreted as directional ranges intended to support strategic analysis, rather than precise measures of readiness.

Table 5: Indicative Maturity Assessment of AI, Autonomy, and Robotics Capabilities

Capability	Space Function	TRL	MRL	Mkt-RL	Illustrative Case
Sensing, Data Fusion & Perception	Integrates imagery, telemetry, navigation, and environmental data to support situational awareness and enable informed, timely decision-making	6–8	6–7	6–7	NASA's Perseverance Rover ¹⁹ demonstrated onboard autonomy for navigation and hazard avoidance, including AI-supported route planning and execution on Mars
Onboard and Edge AI Computing	Enables onboard processing and decision-making to reduce reliance on downlink and allow continued operation under limited or delayed ground contact	6–7	6–7	5–6	ESA PhiSat-2 ²⁰ mission demonstrated onboard AI for EO, including cloud filtering, vessel detection, and data compression to enable reduced downlink dependency and faster data utilization
Autonomy, Guidance Navigation & Control (GNC) & Robotics	Enables autonomous navigation, guidance, and robotic operations, including rendezvous, docking, and in-space servicing, where communication delays or scale limit real-time human control	5–7	5–6	4–5	NASA's OSIRIS-REx ²¹ mission demonstrated autonomous navigation using Natural Feature Tracking to guide precision sampling at Bennu, ²² while commercial RPO and in-orbit servicing systems are advancing through flight demonstration ²³

Capability	Space Function	TRL	MRL	Mkt-RL	Illustrative Case
Health Monitoring & Predictive Maintenance (incl. FDIR)	Enables early anomaly detection, FDIR to support mission continuity in environments where physical intervention is not possible	5–6	5–6	5–6	NASA and ESA have demonstrated autonomous FDIR and AI-enabled telemetry management. Commercial platforms for mission operations are advancing predictive maintenance and anomaly detection capabilities ²⁴
Simulation & Digital Twins	Enables system-level modeling, virtual testing, and performance prediction to reduce reliance on physical testing and support decision-making across the mission lifecycle	6–8	6–8	6–8	Digital twins and virtual engineering environments are widely used in terrestrial industries and are increasingly applied to space system design, mission simulation, and operations, including model-based testing and performance prediction ²⁵
Distributed Autonomy for Constellations and Swarms	Enables coordinated sensing, communications, and task allocation across multiple spacecraft to support scalable, resilient operations without continuous centralized control	4–6	4–5	4–5	NASA Distributed Spacecraft Autonomy ²⁶ research has demonstrated coordinated control and distributed decision-making across multiple spacecraft to advance swarm-based mission architectures ²⁷
Space Safety, SSA & Sustainability	Enables tracking, risk assessment, and mitigation of on-orbit hazards, including conjunction analysis, collision avoidance, and re-entry prediction to support safe, sustainable, and coordinated space operations	6–8	6–8	7–8	ESA has explored machine learning for collision avoidance; ^{28,29} EU SST services cover collision avoidance, re-entry, and fragmentation analysis ³⁰

Space agencies are primarily funding R&D to advance technological and manufacturing readiness, particularly for mission-critical and hardware-constrained applications. In parallel, the commercial sector is establishing the foundations for market-ready solutions, supported by private investment and early customer demand. As a result, a commercial landscape is already emerging across selected segments.

Ground-based AI analytics, geospatial intelligence, digital twins, mission operations, and space traffic management tools are approaching market adoption. In contrast, onboard AI hardware, space-qualified edge computing, autonomous servicing, and distributed autonomy remain more dependent

on flight heritage, standards development, and procurement demand. This divergence reflects both the maturity of underlying technologies and the constraints associated with operating in space environments.

Table 6 illustrates the current commercial solution landscape across key capability areas.

Table 6: Illustrative Commercial Solution Landscape for AI, Autonomy & Robotics

Capability	Commercial Solution Landscape
EO Analytics, Geospatial Intelligence, and Data Fusion	• Privateer: Elements (data fusion platform) • Blackshark.ai: VEOS & REPLIKA (3D reconstruction and simulation of the physical world) • Vantor: Hub, Cortex (spatial intelligence platforms) • Capella Space: SAR data enhancement and automated tasking
Onboard & Edge AI Computing	• KP Labs: Antelope (data processing unit for onboard processing) • Ubotica: SPACE:AI (onboard cognitive Earth observation processing) • Ramon.Space: onboard computing, communication, and storage systems for AI applications
Autonomy, GNC & Robotics	• Starfish Space: Otter/Cephalopod (autonomous servicing vehicles) • Astroscale: autonomous RPO, inspection, and servicing
Health Monitoring & Predictive Maintenance (including FDIR)	• Quindar: mission management, command and control • AIKO: AI-powered autonomy and mission operations software • KP Labs: smart mission ecosystem and onboard analytics
Simulation & Digital Twins	• Ansys: Digital Twin/Twin Builder • Dassault Systèmes: Virtual Twin and 3DEXPERIENCE platforms • Siemens: Digital Twin and executable digital twin solutions
Mission Operations & Constellation Control	• GMV: FocusSuite (flight dynamics and mission operations) • Slingshot Aerospace: AI-enabled operational decision support
Space Safety, SSA & Sustainability	• LeoLabs: space traffic management and tracking services • Kayhan Space: autonomous safety-of-flight alerts and decision tools • Slingshot Aerospace: TALOS AI (SSA and decision support) • COMSPOC: SSA software and analytics suite

Overall, maturity levels across AI, Autonomy, and Robotics:

- **TRL: Medium to high (TRL 5–7)**, reflecting mature core AI capabilities and selected robotic systems, while highlighting the need for further validation in dynamic, real-world space environments.
- **MRL: Medium (MRL 4–6)**, reflecting evolving production, integration, and qualification processes for space-grade autonomous systems, which remain limited and lack standardization.
- **Mkt-RL: Divergent across segments**, with software-driven solutions at medium to high readiness (Mkt-RL 5–7), while hardware-driven onboard systems remain emerging (Mkt-RL 4–5). Demand is strongest in government and large-scale commercial constellation operators, although adoption remains constrained by trust, validation, and regulatory requirements.

2.1.3

Key Technical and Operational Barriers

The development of AI, Autonomy, and Robotics in space is constrained by a set of interconnected barriers that collectively slow progress from innovation to deployment. These barriers emerge across the technology stack, from system design and validation to market adoption and regulatory acceptance. Together, they create a compounding effect in which challenges in one area directly constrain progress in another, limiting both scalability and investor confidence.

Workshop findings and survey responses point to five interrelated barriers shaping this landscape. These barriers are structurally linked across technical, operational, market, and governance dimensions. For example, limited computing capacity and restricted access to high-quality datasets make validation more difficult. Weak validation

slows progress toward flight heritage, and limited flight heritage weakens investor and customer confidence.

1. Technical and Resource Constraints

Space-grade AI and autonomous systems must operate under conditions that fundamentally differ from terrestrial environments. Radiation exposure, power limitations, thermal constraints, and limited onboard computer capacity impose strict requirements on system design and performance. These constraints raise the threshold for reliability and resilience, making even well-developed terrestrial solutions difficult to translate directly into space applications.

2. Validation, Testing, and Flight Heritage

The primary challenge is not only developing algorithms but proving that they can perform reliably across unpredictable and extreme conditions. Validation must account for edge cases, sensor degradation, radiation effects, cyber threats, and unstructured environments. Yet, access to high-quality data and simulation environments remains limited. As a result, flight heritage becomes a critical gating factor, but one that is difficult and expensive to obtain because of limited in-space testing opportunities.

This gap is evident when comparing terrestrial and space operations. In sectors such as remote autonomous mining in Australia,³¹ a single operator can control multiple machines at scale, supported by continuous data, connectivity, and iterative testing environments. In contrast, space missions often require multiple operators to manage a single robotic system, reflecting the higher burden of validation, lower tolerance for failure, and limited ability to iterate once deployed.

3. Trust, Certification, and Operational Accountability

Autonomous systems must meet rigorous assurance and verification requirements to be trusted in safety-critical missions. Thus, operators, regulators, and insurers require a clear and testable understanding of how these systems behave under both nominal and off-nominal conditions, including failure

modes and decision boundaries. Without auditable validation, resilient system design and defined human authority thresholds, adoption of advanced autonomy will remain constrained.

4. Market Demand and Commercial Scalability

While the global AI market is expanding rapidly, the space-specific segment remains narrower, more fragmented, and dependent on anchor demand. The United Nations Conference on Trade and Development (UNCTAD) projects that AI will grow from \$189 billion in 2023 to ~\$4.8 trillion by 2033,³² reinforcing AI's position as a leading frontier technology. However, this growth does not directly translate to space applications, where use cases are more specialized and adoption pathways are slower.

Commercial viability in space requires clearer business cases, longer return-on-investment horizons, and stronger demand signals from agencies, operators, and downstream users. Without credible pathways to repeatable revenue and scaled deployment, investors may view space-based AI, autonomy and robotics as technically promising but commercially uncertain.

5. Regulatory, Liability, and Trade Constraints

Regulatory uncertainty and the absence of clear roadmaps continue to limit visibility for developers and investors, weaken confidence in sustained demand, and slow investment in long-term opportunities. While the broad applicability of space technologies expands potential markets, certain technologies may also be subject to export controls and trade restrictions that can limit access to critical components for civil applications. At the same time, stakeholders are not yet aligned on certifiable and operationally acceptable AI frameworks for space missions, particularly for safety-critical applications. This is compounded by institutional reluctance to adopt systems perceived as opaque or vulnerable to cyber risks, reinforcing a cautious approach to deployment.

Autonomous decision-making in spacecraft raises unresolved questions around authorization, supervision, operator

responsibility, liability allocation, insurance, and cybersecurity. Under existing international space law, including the Outer Space Treaty, states retain responsibility for national space activities even when autonomous systems are used, raising important questions around oversight and liability allocation. Together, these factors slow adoption by increasing perceived risk, constraining access to critical inputs, and limiting confidence in scalable deployment pathways.

2.1.4

Market Potential and Strategic Relevance

AI, Autonomy, and Robotics are core enablers of the space economy, not standalone markets. Their value lies in their ability to transform mission execution, operational efficiency, and system resilience across the entire space ecosystem. Demand is concentrated in sectors where speed, reliability, and data-driven decision-making are critical. This is reinforced by survey inputs, which consistently identified government, strategic, EO, satellite communications, exploration, and safety and sustainability applications as primary demand drivers, reflecting both market needs and strategic priorities.

AI enhances satellite performance through intelligent tasking, onboard data triage, anomaly detection, and collision-risk management, while optimizing the use of power, bandwidth, and human oversight. Autonomy is essential in environments constrained by latency and limited communication, enabling spacecraft to operate and respond independently. In strategic and high-risk operational contexts, these capabilities deliver real-time decision support, resilience, and distributed sensing in contested or degraded environments. For ISAM and OSAM, autonomy and robotics enable the execution of complex tasks,

including inspection, proximity operations, docking, manipulation, and in-space assembly.

Adoption is shaped by mission criticality and risk tolerance. Software-led capabilities scale faster due to lower integration barriers, while onboard and autonomous systems require higher levels of validation and operational trust. This divergence must remain explicit to avoid overstating near-term market readiness. Government and strategic requirements act as primary catalysts for early adoption. These requirements accelerate investment, validate high-value use cases, and establish pathways for broader commercial deployment. As a result, they are likely to play a defining role in shaping early market structure and setting performance benchmarks for wider uptake.

2.1.5

Cross-Cutting Applications

AI, Autonomy, and Robotics have strong cross-cutting potential because they operate as enabling capabilities rather than sector-specific solutions. Their value lies in how they transfer across environments, allowing technologies developed for terrestrial industries to be adapted for space, while space-driven innovations extend to high-value applications on Earth. This bidirectional flow is central to accelerating both market development and technological maturity.

A significant portion of the capability base already exists in terrestrial sectors. Industries such as mining, energy, logistics, advanced manufacturing, remote infrastructure operations, and life sciences rely on automation, robotics, digital twins, predictive maintenance, and AI-enabled decision-making. These capabilities can be adapted to meet space constraints, particularly for missions requiring remote operations, high reliability, and limited human intervention.

In parallel, space-based developments generate downstream value across terrestrial

markets. Capabilities such as onboard data processing, autonomous prioritization, resilient navigation, and distributed sensing are designed for extreme, resource-constrained environments. These same characteristics make them directly applicable to terrestrial use cases that require sustained reliability, including disaster response, climate adaptation, precision agriculture, and critical infrastructure monitoring.

The interaction between spin-in and spin-off pathways is further enabled by cross-sector platforms, as illustrated in Table 7. Test beds, regulatory sandboxes, challenge missions, and mission-driven procurement mechanisms play a critical role in connecting space operators with non-space industries. These platforms expand the addressable market by activating demand from actors that do not traditionally identify as part of the space sector but possess relevant capabilities, data, and operational expertise.



Table 7: Cross-Sector Spin-in and Spin-off Pathways for AI, Autonomy, and Robotics

Application Pathway	Space Use Cases	Terrestrial Spillovers (non-space demand)
Spin-In from Terrestrial Industry	Remote operations for lunar and planetary surfaces; robotic inspection and maintenance; autonomous construction; predictive maintenance; drilling, excavation, and ISRU	Mining automation; energy infrastructure; offshore and remote-site operations; logistics; manufacturing quality control; and robotics for hazardous environments
Spin-Off From Space Capabilities	Onboard EO data triage; autonomous data prioritization; resilient navigation; satellite-enabled monitoring; distributed sensing and edge processing	Disaster response; climate adaptation; precision agriculture; food and water management; smart-city systems; critical infrastructure resilience and environmental compliance
Cross-Sector Innovation Platforms	Shared testbeds; regulatory sandboxes; challenge missions; mission-driven procurement linking space operators with non-space firms	Demand creation among non-space actors with relevant capabilities, including data, materials, robotics, and operational expertise

2.1.6

Time to Maturity

Time to maturity varies by use case, reflecting differences in risk tolerance, system criticality, and validation requirements. Near-term adoption is driven by software-led applications, while longer timelines are associated with safety-critical autonomy that requires high assurance and flight heritage.

Estimated Maturity Timelines:

1–3 years: Ground-based AI applications for mission operations, engineering knowledge support, EO analytics, digital twins, tasking support, anomaly detection, and decision support. These use cases scale faster because they operate under human oversight and face lower barriers to integration and certification.

3–5 years: Expanded deployment of onboard and edge AI for payload-data triage, cloud filtering, autonomous instrument tasking, and supervised onboard autonomy within defined operational envelopes. Adoption depends on demonstrated reliability in orbit and incremental increases in autonomy under controlled conditions.

5–10+ years: Safety-critical autonomous capabilities, including maneuver execution, distributed swarm coordination, autonomous RPO/docking, complex robotic servicing, in-space assembly, and deep-space robotic operations. These systems require standards and repeated in-orbit validation to build operational trust.

2.1.7

Acceleration Measures

Acceleration of maturity depends on coordinated technical, regulatory, and market actions, including:

- System-level demonstrations and in-orbit testbeds to build space heritage, validate performance, and establish operational trust.
- Shared datasets, high-fidelity simulation environments, and digital twins to support scalable training, validation, and assurance.
- Standardized frameworks for verification, validation, transparency, interpretability,

cybersecurity, and certification to enable interoperability and reduce fragmentation.

- Clear regulatory pathways defining authorization, continuing supervision, autonomous decision thresholds, liability, insurance, and cyber and data governance.
- Government anchor procurement, public-private partnerships, and mission-driven funding to clarify demand signals and reduce investor risk.

- National or regional “sandbox in space” environments, such as a shared small satellite testbed (e.g., ESA PhiSat mission) to enable in-orbit experimentation by multiple ecosystem actors.
- Cross-sector use case generation to expand addressable markets beyond space and establish credible spin-in and spin-off pathways.



2.2

In-Space and On-Orbit Servicing, Assembly & Manufacturing

ISAM and OSAM underpin a shift toward serviceable, scalable infrastructure, extending asset lifespans, reducing replacement cycles, and enabling in-space construction at scale.

2.2.1

Definition

In-Space Servicing, Assembly, and Manufacturing (ISAM) is a cluster of technologies and operational capabilities that enable the servicing, construction, and production of space systems in space, including Earth orbit and deep-space environments. It represents a system-level evolution in how space assets are designed, deployed, and maintained, moving from single-use architectures to modular, adaptable infrastructure. This broader framing reflects how capabilities are expected to operate across Earth orbit, cislunar space, and future deep-space environments.

On-Orbit Servicing, Assembly, and Manufacturing (OSAM) represents the most operationally mature segment of the ISAM capability set, where technical feasibility, commercial pathways, and early demand are already being established. It concentrates near-term activity in Earth orbit, where existing assets, infrastructure, and market needs create immediate use cases for intervention, upgrade, and extension. As a result, OSAM functions as the proving ground for capabilities that will later scale

across the broader ISAM landscape.

Based on the survey, ISAM and OSAM are defined by a set of capabilities that span both asset life extension and infrastructure creation. These capabilities include inspection and diagnostics, maintenance and repair, refueling and life extension, repositioning and orbital transfer through tugging, and upgrading or retrofitting of existing systems. The survey further identifies in-space assembly of large structures and modular spacecraft, in-space manufacturing of components and materials, and end-of-life disposal and debris mitigation as integral functions of this technology cluster. These capabilities operate across two reinforcing dimensions. The first focuses on maximizing the value and performance of existing assets through servicing, extension, and optimization. The second enables the creation of new infrastructure in space through assembly and manufacturing, allowing systems to be built, adapted, and scaled beyond the mass and volume constraints of launch. Together, they redefine how space systems are deployed, maintained, and evolved.

In practical terms, the survey findings indicate a structural shift away from single-use architectures toward modular, serviceable, and scalable systems. This reduces dependence on full system replacement,

increases operational flexibility, and enables the deployment of assets that are too large, complex, or costly to launch as integrated units. It also introduces new operational layers, including in-space logistics, maintenance cycles, and infrastructure management, which were previously limited in the space economy.

This technological cluster depends on a set of enabling layers that underpin its technical and operational feasibility, including:

- RPO
- Precise navigation and guidance
- Robotic capture and manipulation
- Standardized interfaces
- Modular spacecraft design
- Space-grade tools
- Propellant-transfer systems
- Verification and safety procedures
- Clear rules for authorization, responsibility, liability, and insurance

The need for these capabilities is driven by the limitations of current space systems, which are largely designed as single-use assets with limited capacity for upgrade, repair, refueling, or direct robotic interaction after deployment. ISAM and OSAM address these constraints by enabling post-launch intervention, adaptation, and extension of space assets. This fundamentally changes the lifecycle assumptions, shifting from static, predefined missions to dynamic, evolvable systems.

This positioning is reinforced by institutional and policy perspectives. NASA defines ISAM as a broad set of capabilities supporting civil, national interests, and commercial missions, including robotic manipulation, RPO, manufacturing, and in-space logistics.³³ Similarly, the United States' ISAM National Strategy identifies ISAM as foundational for sustained economic activity³⁴ and long-term human presence in space³⁵ by enabling the development of persistent in-space platforms and infrastructure.

At the international level, multiple states are actively advancing ISAM and OSAM capabilities, but visibility is low due to their strategic sensitivity. China is pursuing initiatives in orbital refueling, life extension, space tugging, robotic manipulation, and station assembly. India is progressing through the Space Docking Experiment (SpaDeX) mission,³⁶ demonstrating autonomous rendezvous, docking, undocking, and inter-satellite power transfer in orbit. Russia has also conducted several robotic RPO tests, many of which are associated with strategic applications.³⁷

As a result, ISAM and OSAM may be viewed as an enabling layer for the next phase of the space economy rather than a standalone capability domain. Their value lies in how they reshape system design, extend asset utility, and support the development of persistent space infrastructure. This positions ISAM and OSAM as a foundational component for scaling future commercial, civil, and exploration activities.

2.2.2

Maturity Level

The maturity of ISAM and OSAM remains uneven across the technology cluster. Some on-orbit servicing capabilities have already demonstrated operational value, particularly satellite life extension in GEO. Northrop Grumman's SpaceLogistics Mission Extension Vehicle,³⁸ for example, has performed commercial life-extension services for GEO satellites using proximity sensors and mechanical docking with client satellites.

This progress, however, should not be read as maturity across the full ISAM and OSAM landscape. More complex functions, including refueling of unprepared satellites, in-space manufacturing, modular upgrades, and large-scale assembly, remain at earlier stages of development. These capabilities require further in-orbit demonstration,

standardized interfaces, technical assurance, and market validation before they can be adopted at scale.

As seen in Figure 4, the survey results reflect this mixed maturity profile. ISAM and OSAM scores are 3.00/5 for technology readiness, 3.43/5 for market readiness, 2.43/5 for policy fit, 2.86/5 for time to maturity, and 3.71/5 for cross-cutting potential. The average score of 3.09/5 indicates credible momentum and strategic relevance yet emerging overall operational maturity.

The highest score, cross-cutting potential, suggests that experts see ISAM and OSAM as applicable beyond a narrow servicing market. Its value extends to satellite operations, exploration architectures, space logistics, debris mitigation, infrastructure development, and future commercial platforms. This potential reinforces the view that ISAM and OSAM are strategically important even where individual capabilities remain technically or commercially under development.

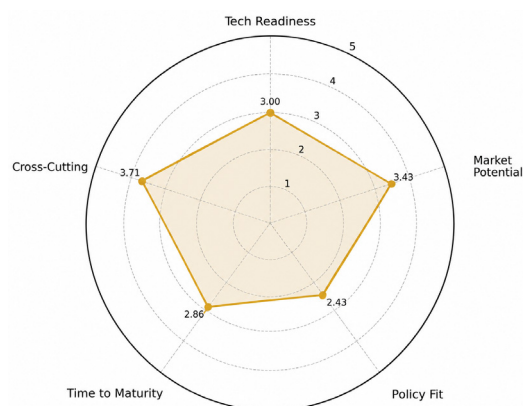


Figure 4: Maturity level for ISAM and OSAM technologies, CSF survey results, 2025

The lower scores for policy fit and time to maturity point to the main constraints on adoption. ISAM and OSAM depend on clear rules for authorization, liability, responsibility, insurance, safety, and proximity operations, as many of these activities involve direct interaction with another space object. Without stronger governance frameworks and standardized technical interfaces, the

pace of deployment will remain slower than strategic demand suggests.

Overall, the maturity profile shows a technology cluster with strong long-term potential but uneven near-term readiness. Commercial life extension has moved from demonstration to operational use, while manufacturing, refueling, modular upgrading, and large-scale assembly still require demonstration at higher scale and complexity. The next phase of maturity will depend less on isolated technical demonstrations and more on integrated missions that collectively validate business models, standards, safety procedures, and regulatory pathways.

The maturity levels in Table 8 are indicative expert estimates on a 1–9 scale based on public demonstrations, program status, and visible commercial offerings. They should be read as directional indicators rather than definitive readiness classifications. This is especially important for ISAM and OSAM because public visibility is uneven, strategically sensitive applications may be partially classified, and maturity varies significantly across servicing, assembly, manufacturing, logistics, and disposal.



Table 8: Indicative Maturity Assessment of ISAM and OSAM Capabilities

Capability	Stage of Adoption	TRL	MRL	Mkt-RL	Commercial Solution	Illustrative Case
Satellite Life Extension and Station-Keeping Support	Operationally demonstrated, with an early commercial market	9	7–8	3–5	Limited and operational	Northrop Grumman's SpaceLogistics MEV-1 ³⁹ docked with Intelsat IS-901 in 2020, and MEV-2 docked with Intelsat IS-10-02 in 2021 to provide life-extension services
RPO and Docking (RPOD)	Demonstrated across several mission contexts, with commercial validation expanding	7–8	6–7	5–6	Emerging	China launched Shijian-25 ⁴⁰ in January 2025 to verify satellite fuel-replenishment and life-extension technologies. ESA's RISE mission with D-Orbit ⁴¹ is planned to demonstrate safe rendezvous and docking with a GEO client satellite, supporting future commercial life-extension services
Autonomous RPO Software and GNC	In-orbit validation and early product development	7–8	6	3–5	Emerging	NASA's 2025 State of Play identifies Starfish Space's CEPHALOPOD as commercial RPOD software. Starfish Space and Impulse Space also reported the Remora autonomous RPO demonstration in LEO in 2025
Inspection and Metrology of Satellites and Debris	Demonstrated, with service models emerging	7–8	6	5	Emerging	JAXA's CRD2 Phase I and Astroscale's ADRAS-J ⁴² demonstrated fly-around observation and imaging of a non-cooperative debris object
Robotic Capture and Active Debris Removal	Demonstration stage, mainly supported by agency-backed commercial missions	6–7	5–6	4–5	Emerging, not yet routine	ESA's ClearSpace-1 ⁴³ is designed to remove the PROBA-1 satellite as an unprepared, non-cooperative object through complex close-proximity operations

Capability	Stage of Adoption	TRL	MRL	Mkt-RL	Commercial Solution	Illustrative Case
Robotic Manipulation and Space-rated Tools	Mature on crewed platforms, but less mature for free-flying servicing applications	6–8	5–6	4–5	Partial	Robotic manipulation includes grappling spacecraft, placing modules, cutting, welding, moving components, and deploying large structures. ISS heritage is strong, and commercial free-flying applications are still emerging
Refueling and Fluid Transfer	Interface products are emerging, while orbital service demonstrations remain early	5–8, depending on the subsystem	5–6	3–5	Available for selected interfaces; the service market is still emerging	Orbit Fab markets RAFTI as a TRL 8 cooperative docking and refueling interface. ⁴⁴ Under a US Space Force award, ⁴⁵ Northrop Grumman's Elixir/Tetra-6 demonstration pairs a service vehicle with a client spacecraft, using active and passive refueling modules to validate on-orbit fuel transfer
Repair, Upgrade, and Modular Replacement	Early demonstration and R&D stages	4–6	3–5	2–4	Limited	NASA's discontinued OSAM-1 ⁴⁶ illustrates both technical ambition and difficulty with adoption. NASA ended the project citing technical, cost, schedule, and partner-demand issues
In-space Assembly of Large Structures	Demonstrated through crewed spaceflight, while autonomous assembly remains early	5–7	4–5	2–4	Limited	Relevant applications include large telescopes, stations, solar arrays, and cislunar platforms. NASA classifies assembly as one of the core ISAM capability areas
In-space Additive Manufacturing and Orbital Production	Operational for select materials, with broader applications still early	7–8 for polymer AM on ISS; lower for advanced applications	5–6	4–5	Niche	Redwire's Additive Manufacturing Facility ⁴⁷ has operated on the ISS since 2016, producing tools, assets, and parts in orbit for government and commercial customers

Capability	Stage of Adoption	TRL	MRL	Mkt-RL	Commercial Solution	Illustrative Case
In-space Logistics, Tugging and Repositioning	Commercially emerging, but still fragmented across use cases	7–8	6	5–6	Emerging	This capability area includes repositioning, orbital transfer, disposal support, and the logistics layer needed for more serviceable space infrastructure
Standardized Servicing Interfaces and Modular Spacecraft Design	Early market formation, with standardization remaining a key bottleneck	5–8 depending on the interface	5–6	4–5	Available for select interfaces	RAFTI ⁴⁸ and Northrop Grumman's Passive Refueling Module illustrate early standardization pathways. However, the broader market still lacks common servicing interfaces across satellite classes

2.2.3

Key Technical and Operational Barriers

ISAM and OSAM experience a distinct maturity challenge because their core functions require direct physical or operational interaction with space assets after launch. Unlike many space technologies that can be integrated into a mission before deployment, ISAM and OSAM often depend on approaching, inspecting, docking with, manipulating, refueling, upgrading, or relocating an asset already in orbit. This makes the technology cluster highly sensitive to spacecraft design, mission authorization, operator consent, collision risk, and the target object's behavior.

1. Close-Proximity Operations and Physical Interaction Risk

RPOs, capture, docking, berthing, and robotic manipulation are among the most difficult operational requirements for ISAM and OSAM. A servicing spacecraft must approach and operate around another space object without causing collisions, contamination, signal interference, plume disturbances, or mission disruptions. These risks increase when the target is

non-cooperative, tumbling, unprepared for servicing, unable to provide navigation or docking support, or located in a congested orbital regime.

This challenge is central because ISAM and OSAM missions involve reaching another object and interacting with it safely. Inspection, refueling, repair, tugging, debris removal, and modular replacement all depend on controlled proximity operations and reliable contact dynamics. The operational threshold is therefore higher than conventional satellite missions because failure can affect the servicer, the client asset, and the surrounding orbital environment.

2. Legacy Satellite Design and Lack of Serviceability

Most satellites were not designed to be serviced after launch. Many lack grappling fixtures, refueling ports, standard docking interfaces, accessible components, modular payload bays, and software or data protocols that enable safe interaction with a service vehicle. This forces service providers to design around bespoke spacecraft configurations, increasing mission complexity, cost, and risk.

This barrier is consistent with the survey findings that ISAM and OSAM require standardized interfaces and modularity. The transition from tailored demonstrations to repeatable, scalable services therefore

depends on adopting common interface requirements and serviceable design principles. The absence of serviceability across the existing satellite base limits scalability, even as servicing technologies continue to advance.

3. Verification, Qualification, and In-Orbit Demonstration

ISAM and OSAM operations are difficult to validate fully before flight. Ground testing cannot fully reproduce orbital dynamics, lighting variability, thermal cycling, plume effects, autonomous system responses to unexpected scenarios, contact dynamics, or abnormal target behavior. This creates a validation gap for missions that require autonomous approach, robotic capture, docking, fuel transfer, or physical manipulation of another space object.

The workshop discussion identified qualification and knowledge gaps, limited access to relevant test infrastructure, and insufficient opportunities for in-space demonstration as recurring constraints. For ISAM and OSAM, this is especially important because maturity depends on validating full operational sequences rather than isolated subsystems. A mission may have mature sensors, robotics, and propulsion, yet remain commercially immature if the complete servicing chain has not been demonstrated under realistic orbital conditions.

4. Rules for Authorization, Liability, and Insurance

The legal and operational environment has not yet caught up with missions that intentionally approach, dock with, repair, refuel, reposition, or remove other space objects. ISAM and OSAM raise questions around authorization, continuing supervision, client consent, liability and responsibility for damage, insurance allocation, cybersecurity, and transparency of close-proximity operations. These questions become more complex when missions involve non-cooperative targets, cross-border ownership, strategically sensitive assets, or physical contact with another operator's spacecraft.

The survey explicitly identified the need for clearer "traffic rules" for satellites conducting servicing and proximity operations. These

include operating permissions, safety procedures, notification practices, proximity-operation protocols, liability arrangements, and insurance frameworks. Without these rules, technically feasible missions may still face delays because regulators, insurers, and customers lack a predictable basis for approval and risk allocation.

5. Strategic Sensitivities and Ambiguity

The same capabilities that make ISAM and OSAM valuable for sustainability and infrastructure also create strategic ambiguity. RPO, inspection, tugging, refueling, docking, and robotic manipulations can support life extension, logistics, debris mitigation, and infrastructure development, but they can also resemble or enable counterspace activities. A spacecraft capable of inspecting, refueling, or repositioning a satellite may therefore be interpreted as both a servicing asset and a potential threat, depending on context, transparency, and intent.

A clear example of this concern is China's Shijian-21 mission, which relocated a derelict BeiDou satellite into a graveyard orbit. While this demonstrated an orbital relocation capability with potential debris-management value, it also attracted security scrutiny because it involved a close approach and movement of another space object. Shijian-25,⁴⁹ reported as a Chinese satellite for orbital refueling and life-extension technologies, reinforces the argument that servicing demonstrations can advance sustainability and logistics objectives while also raising concerns over intent, transparency, and potential offensive applications.

6. Market Formation and Serviceability Incentives

The commercial market is more likely to scale as servicing capacity and serviceable demand develop together. Service providers need enough compatible satellites to justify investment, while satellite operators need reliable servicing providers before redesigning spacecraft for serviceability. The US Government Accountability Office (GAO)⁵⁰ describes this as a "chicken-and-egg" problem, in which both sides hesitate because the other has not yet reached sufficient maturity. This is reinforced by

limited in-space test opportunities, unclear servicing standards, uncertain serviceability requirements, and still-evolving commercial models.

NASA's discontinued OSAM-1⁵¹ mission illustrates the gap between technical ambition and executable implementation. The project faced technical, cost, schedule, and partner-demand challenges, showing that adoption requires more than a promising capability. Scalable deployment depends on credible customers, disciplined mission scope, standardized interfaces, and a clear route to repeatable demand.

Taken together, these barriers show that ISAM and OSAM are constrained less by one missing breakthrough than by the difficulty of turning space assets into serviceable infrastructure. The technology requires capable servicers, satellites designed for servicing, clearer regulations for close-proximity operations, insurers willing to price the risk, and customers willing to pay for life extension, refueling, repair, or disposal. This makes their maturity highly dependent on coordination between spacecraft designers, operators, regulators, insurers, agencies, and commercial service providers.

2.2.4

Market Potential and Strategic Relevance

The market potential for ISAM and OSAM is driven by the growth of satellite populations, the rising value of orbital infrastructure, and the need to preserve assets in increasingly congested and contested space environments. As more critical systems operate in orbit, demand for inspection, anomaly response, collision-risk management, life extension, disposal, refueling, repair, and servicing is expected to grow. This positions ISAM and OSAM as both a commercial opportunity and a strategic capability for protecting and extending the value of space assets.

Public market estimates vary significantly due to inconsistent definitions of market scope across sources. Some reports assess only on-orbit satellite servicing, while others include in-space manufacturing, servicing, transportation, and broader infrastructure development. The figures in Table 9 should therefore be treated as directional indicators of market momentum rather than exact forecasts.



Table 9: Overview of Select Market Report Insights into ISAM and OSAM

Source	Market Scope	Market Size and Growth Estimate	Interpretation for ISAM and OSAM
MarketsandMarkets ⁵²	On-orbit satellite servicing	\$2.4B (2023) to \$5.1B (2030), CAGR 11.5%	Indicates a near-term servicing market driven by mission-extension vehicles, debris concerns, and autonomous servicing capabilities
Global Market Insights ⁵³		\$2.7B (2024) to \$8.0B (2034), CAGR 11.6%	Reinforces steady double-digit growth driven by satellite constellations, space traffic management needs, robotics, automation, and debris management
Precedence Research ⁵⁴		\$4.7B (2025) to \$12.6B (2035), CAGR 10.4%	Suggests broader market growth across active debris removal, robotics servicing, refueling, and assembly-related applications
Strategic Market Research ⁵⁵	In-space manufacturing services	\$3.6B (2025) to \$11.7B (2035), CAGR 12.4%	Indicates growing interest in space-for-space and space-for-Earth manufacturing, including semiconductors, pharmaceuticals, nanomaterials, life sciences, and 3D manufacturing
Wise Guy Reports ⁵⁶	In-space manufacturing, servicing, and transportation	\$21.3B (2030) to \$135.3B (2040), CAGR 20.3%	Represents a broader, longer-term infrastructure market with stronger growth assumptions across manufacturing, servicing, transportation, and in-space logistics

Table 9 points in a broadly consistent direction even though the numerical estimates are not directly comparable due to differences in market scope. Studies adopting a narrower market definition anticipate a growing near-term servicing market, particularly in life extension, inspection, debris mitigation and removal, and autonomous servicing. In contrast, broader market estimates indicate a long-term opportunity in which servicing, manufacturing, transportation, and logistics converge into an integrated in-space infrastructure market.

The survey findings similarly characterize ISAM and OSAM as an emerging technology cluster that is steadily gaining momentum. However, this momentum does not yet translate into large-scale investment, as the sector continues to face long ROI timelines, high capital expenditure requirements, evolving business models, technical complexity, regulatory uncertainty, and

limited visibility into sustained, repeatable demand. This means that ISAM and OSAM have strong strategic relevance, but commercial adoption will remain concentrated in use cases where customers, standards, and operational pathways are more clearly defined.

Government demand is likely to provide an important early anchor market, reflecting the high value governments place on technological resilience, rapid response, mission continuity, inspection, maneuverability, and recovery capabilities. Workshop discussions consistently identified strategic government use cases as key demand drivers that can accelerate technology maturity and support market development. Early government demand can help validate capabilities, absorb higher initial costs, and support the transition from demonstration to operational use.

Furthermore, ISAM and OSAM should not be viewed solely through the lens of commercial satellite servicing. Recent missions and programs, including China's Shijian-25, India's SpaDeX, and Japan's CRD2 mission, show that states are advancing these capabilities as part of strategic, operational, and sustainability agendas. Even where commercial markets mature slowly, these developments indicate that ISAM and OSAM are becoming a strategic capability linked to future infrastructure, orbital sustainability, national resilience, and long-term access to space.

Overall, the evidence suggests that the market potential for ISAM and OSAM is substantial but uneven across time horizons and application areas. Near-term opportunities are strongest in life extension, inspection, disposal, selected logistics services, and government-backed demonstration missions. Longer-term value will depend on their ability to transition from bespoke, mission-specific operations to standardized, repeatable, and commercially sustainable infrastructure services.

2.2.5

Cross-Cutting Applications

ISAM and OSAM are cross-cutting enablers that affect how space assets are sustained, upgraded, repositioned, and expanded after launch. Their near-term relevance is strongest in space sustainability, where life extension, post-mission disposal, inspection, and active debris removal can reduce replacement cycles and support safer orbital operations. They also strengthen space communications and data infrastructure by enabling maintenance, relocation, anomaly response, and resilience for critical orbital assets.

Over the long term, ISAM and OSAM can enable modular construction, in-space logistics, large platforms, fuel depots, and future cislunar or deep-space architectures

that may be difficult or inefficient to deploy through launch-only models. Their value is therefore not limited to satellite servicing but extends to exploration systems, orbital platforms, and future infrastructure beyond Earth. This makes them a connecting capability across sustainability, communications, exploration, and space infrastructure.

Moreover, ISAM and OSAM are closely linked to the other emerging space technology clusters identified in this report. AI and autonomy enable the precision, responsiveness, and decision-making required for proximity operations, inspection, docking, and robotic manipulation. Their deployment also depends on advances in propulsion, power, avionics, thermal systems, communications, and on-orbit data infrastructure. Future space resources and ISRU systems will also rely on ISAM and OSAM to construct, maintain, and repair infrastructure beyond Earth orbit.

Beyond the space sector, ISAM and OSAM can generate spillovers into industries operating in remote, hazardous, or difficult-to-access environments. Relevant functions include advanced robotics, remote maintenance, autonomous inspection, digital twins, modular industrial design, precision logistics, and high-reliability manufacturing. These capabilities apply to offshore energy, aviation maintenance, mining automation, critical infrastructure, and hazardous-environment operations.

Workshop discussions reinforced that progress across priority technologies will depend on system-level enablers rather than isolated capabilities. For ISAM and OSAM, this means cross-cutting value will come from integrating robotics, autonomy, software-defined architecture, miniaturization, and resilient communications. Together, these capabilities make space systems more serviceable, adaptable, and scalable across multiple mission domains.

2.2.6

Time to Maturity

Time to maturity for ISAM and OSAM varies significantly by capability, reflecting differences in technical complexity, target readiness, safety risk, and market demand. Near-term adoption is likely to concentrate on services that do not require extensive modification of client spacecraft, while longer timelines apply to refueling, modular upgrades, large-scale assembly, and manufacturing. The pace of maturity will depend on whether the sector can move from isolated demonstrations to repeatable services supported by standardized interfaces, regulatory clarity, and credible customer demand.

Estimated Maturity Timelines:

3–5 years: Operational growth is most likely in inspection, life extension, relocation, selected docking demonstrations, and disposal-support services for high-value assets. These applications have clearer near-term demand because they address asset preservation, mission continuity, anomaly response, and orbital sustainability. They can also build on existing commercial and institutional demonstrations, making them the most credible segment for early operation within ISAM and OSAM.

5–8 years: Broader servicing of prepared satellites, refueling demonstrations, modular upgrades, and routine proximity-operation services may mature as more spacecraft are deliberately designed for serviceability. Adoption in this period will depend on standardized interfaces, cooperative client spacecraft, validated safety procedures, and clearer authorization pathways. Government anchor procurement, co-funded demonstrations, and early service contracts will be important for reducing market uncertainty and supporting repeatable deployment.

8–10+ years: Large-scale in-space assembly and manufacturing are likely to require longer timelines because they depend on advances in robotics, autonomy, materials, power,

logistics, quality assurance, and orbital infrastructure. These capabilities also need sustained demand from large platforms, fuel depots, cislunar systems, and deep-space architectures. Their maturity will depend less on single demonstrations and more on an ecosystem capable of supporting construction, verification, maintenance, and operations in space.

2.2.7

Acceleration Measures

Acceleration of maturity depends on coordinated, technical, regulatory, and market actions, including:

1. Anchor Demand and Mission-Linked Procurement

Governments and large institutional buyers should create credible demand signals through service contracts, anchor procurement, mission-aligned co-funding, and early adoption of ISAM and OSAM services. The US ISAM National Strategy explicitly recognizes the need to provide sustained demand signals and prepare for procurement of ISAM capabilities. This is essential because the market scales based on demonstrated value rather than technical promise alone.

2. Standardized Interfaces and Serviceable Spacecraft Design

The sector should move toward common grappling points, refueling ports, docking mechanisms, accessible components, modular payload bays, and interoperable software and data interfaces. Workshop findings and survey inputs consistently point to standardization and modularity as core acceleration measures. Without these design shifts, ISAM and OSAM risk remaining expensive, bespoke, and difficult to scale.

3. System-Level Demonstrations and In-Space Testbeds

The sector needs repeated demonstrations that validate full mission sequences, including RPO, docking, robotic manipulation, servicing, autonomy, and safe departure. Shared testbeds and in-space “sandbox” environments can reduce duplication, increase flight heritage, and build confidence among operators, regulators, insurers, and investors. The priority is not only to prove individual subsystems, but to validate integrated operations under realistic orbital conditions.

4. Clear Authorization, Liability, and Insurance Pathways

Regulators should develop clearer approval processes for ISAM and OSAM missions. These pathways address safety procedures, consent requirements, transparency measures, liability allocation, insurance expectations, cybersecurity requirements, and post-mission disposal obligations. Such measures would enable customers and insurers to assess risk before committing themselves to operational services.

5. Public-Private Partnerships and International Coordination

ISAM and OSAM are too complex and capital-intensive to mature through isolated projects. Progress requires coordination among agencies, satellite operators, insurers, manufacturers, launch providers, robotics firms, standards bodies, and governmental stakeholders. International confidence-building measures are also important because close-proximity operations can raise strategic ambiguity if intent, notification, and operations are unclear.

6. Validated Business Models and Revenue-Linked Use Cases

The investment case should be strengthened through milestones tied to real customer value, including life extension, revenue preservation, anomaly recovery, disposal support, inspection-as-a-service, refueling, and mission assurance. Aligning with customer value directly addresses investor concerns about weak business models, long ROI timelines, high CAPEX, and

uncertain demand. The strongest near-term opportunities will be those that clearly protect revenue, reduce replacement costs, or manage operational risk.



2.3

Advanced Propulsion and Space Power Systems

Advances in propulsion and power will expand the scale, duration, and reach of space activity, but their impact will depend on how effectively they are integrated into complete mission architectures.

2.3.1

Definition

Advanced propulsion and space power systems refer to the technologies that enable spacecraft and space infrastructure to move, maneuver, generate energy, store power, distribute electricity, and sustain operations over time. Propulsion systems determine a mission's mobility, including orbit raising, station-keeping, collision avoidance, deorbiting, RPO, cislunar transfer, and deep-space travel. Power systems determine a mission's endurance and functional capacity by supporting payloads, communications, onboard computing, electric propulsion, thermal regulation, robotics, autonomy, ISRU, and long-term operations.

This cluster brings propulsion and power together because their performance is increasingly interdependent. Electric propulsion (EP), for example, depends not only on thruster efficiency but also on the availability of sustained electrical power, power-processing units, thermal management, and mission-level power allocation. Future high-power spacecraft, space transport vehicles, lunar surface assets, and deep-space missions will require propulsion and power architectures

that are designed as integrated systems rather than isolated subsystems. Together, advanced propulsion and space power form the mobility and energy foundation of next-generation space missions, shaping the reach, endurance, responsiveness, and operational scale of future space activities.

Table 10 outlines the technology scope and main breakthrough priorities across the advanced propulsion and space power systems stack.

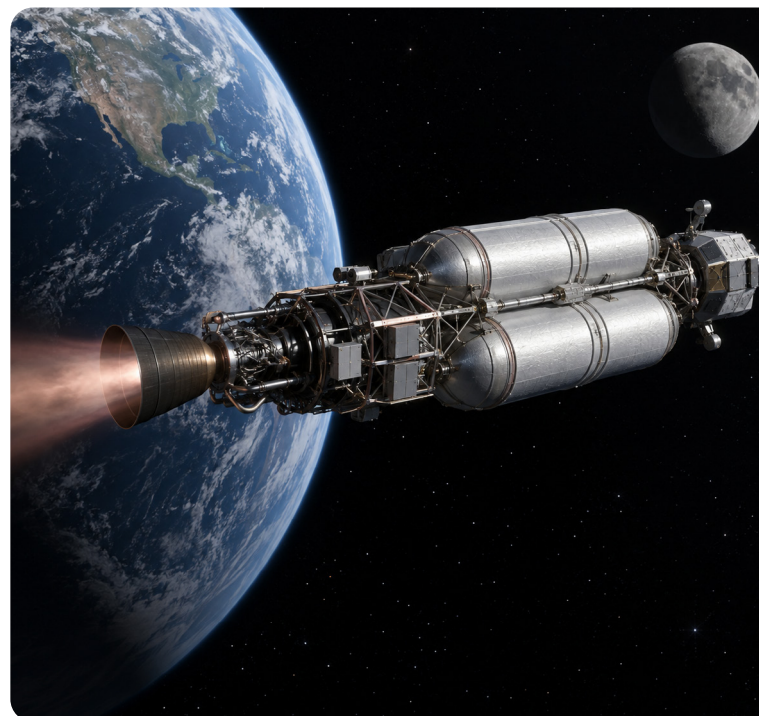


Table 10: Overview of Breakthrough Priorities for Advanced Propulsion and Space Power Systems

Technology	Scope of Cluster	Main Breakthroughs Required
Advanced Propulsion Systems	Chemical and Green Propulsion: • High efficiency chemical propulsion • Rotating Detonation Rocket Engines • Non-toxic or lower toxicity propellants • Methane-liquid oxygen systems • Storable propellants • Smallsat chemical propulsion • Multi-mode propulsion	• Higher thrust-to-weight ratios • Safer, more accessible propellants • Improved combustion stability • Better materials for higher chamber temperatures and pressures • Longer-life valves and feed systems • Lower cost integration • Sophisticated injector designs
	EP Systems: • Hall Thrusters • Ion Thrusters • Plasma Propulsion Concepts • Smallsat EP • High Power EP • Power Processing Units	• Higher thruster lifetime • Improved thrust-to-power ratios • Better propellant utilization • Improved cathode and grid durability • Higher system efficiency • Lower-cost power processing units • Scalable qualification for commercial missions
	Nuclear Thermal Propulsion (NTP): • Reactor Heated Hydrogen Propulsion • High Temperature Fuel Element • Cryogenic Hydrogen Storage • Deep Space Transfer Architectures	• Higher fuel element temperature tolerance • Reliable reactor start-up and control • Improved hydrogen compatibility • Stronger safety assurance • Low-boil-off or zero-boil-off liquid hydrogen storage • Improved insulation • Active cooling • Reliable long-duration cryogenic fuel management system
	Nuclear Electric Propulsion (NEP): • Fission Power Sources • Electric Thrusters • Power Conversion Systems • High-Power Processing Units • Long-Duration Deep-Space Propulsion Architecture	• More efficient thermal-to-electric conversion • Lightweight radiators • Better heat rejection • Reliable high-power electric thrusters • Radiation-tolerant power electronics • Integrated reactor-power propulsion validation

Technology	Scope of Cluster	Main Breakthroughs Required
Space Power Systems	• Solar Power • Batteries • Power Electronics • Power Conditioning and Distribution • High-Density Storage • Radioisotope Power Systems • Nuclear Fission Power • Surface Power Systems • In-Space Power Architecture	• Higher energy density • Improved degradation resistance • Better power management • Scalable surface power • Long-duration storage • Reliable operation in harsh environments
Integrated Propulsion Power Systems	• High Power EP • Power Processing Units • NEP • Energy Storage for Maneuvering • Mission-Level Energy Optimization • Power Conversion Units	• Better integration between propulsion and power systems • Greater power availability for EP • Improved energy management for high-power operations • Increased system reliability • Validated architectures for cislunar and deep-space missions

The table highlights that progress in this cluster will depend on more than isolated component improvements. Advanced propulsion and space power systems mature as integrated architectures in which thrust, efficiency, energy availability, storage, power conversion, thermal management, and mission duration are optimized together. The maturity of this cluster will therefore be shaped by both technical performance and system-level readiness, including the ability to qualify, integrate, and operate these technologies reliably across orbital, cislunar, lunar, and deep-space environments.

2.3.2

Maturity Level

Advanced propulsion and space power systems have a medium-to-high overall maturity profile, with maturity varying significantly across technology families and use cases. Conventional chemical propulsion, deployable solar arrays, batteries, power electronics, and power management and distribution systems are already operationally mature and commercially available. EP is also increasingly mature, with growing adoption for station-keeping, orbit raising, orbit transfer, and smallsat mobility.

This maturity profile is uneven because the cluster includes both established operational systems and emerging high-impact architectures. Green propulsion, high-power solar electric propulsion, in-orbit propellant transfer, long-duration cryogenic storage, nuclear thermal propulsion, NEP, fission surface power, and high power-density systems and high energy-density storage systems for lunar and deep-space infrastructure are at lower maturity levels. These technologies are progressing through demonstration, qualification, or program-level development, while still facing constraints related to systems integration, thermal management, safety assurance, regulatory approval, qualification costs, and commercial demand.

The survey reflects this mixed profile, as illustrated by Figure 5. The cluster received a technology readiness score of 3.64/5, market readiness of 4.21/5, policy fit of 3.21/5, time to maturity of 3.50/5, and cross-cutting potential of 3.93/5, resulting in an overall maturity score of 3.70/5. The results place advanced propulsion and space power systems among the more mature and market-relevant priority clusters.

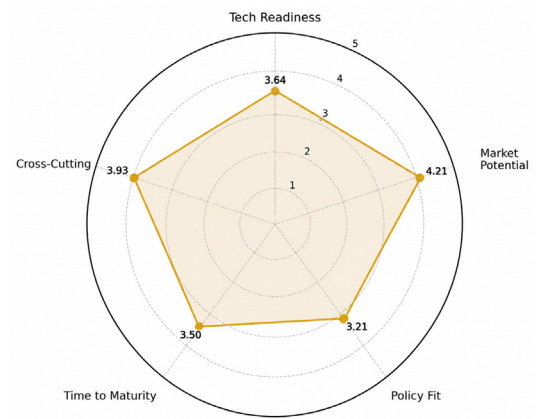


Figure 5: Maturity level for Advanced Propulsion and Space Power Systems, CSF Survey Results, 2025

Table 11 provides an indicative maturity assessment across the main technology families within the cluster.

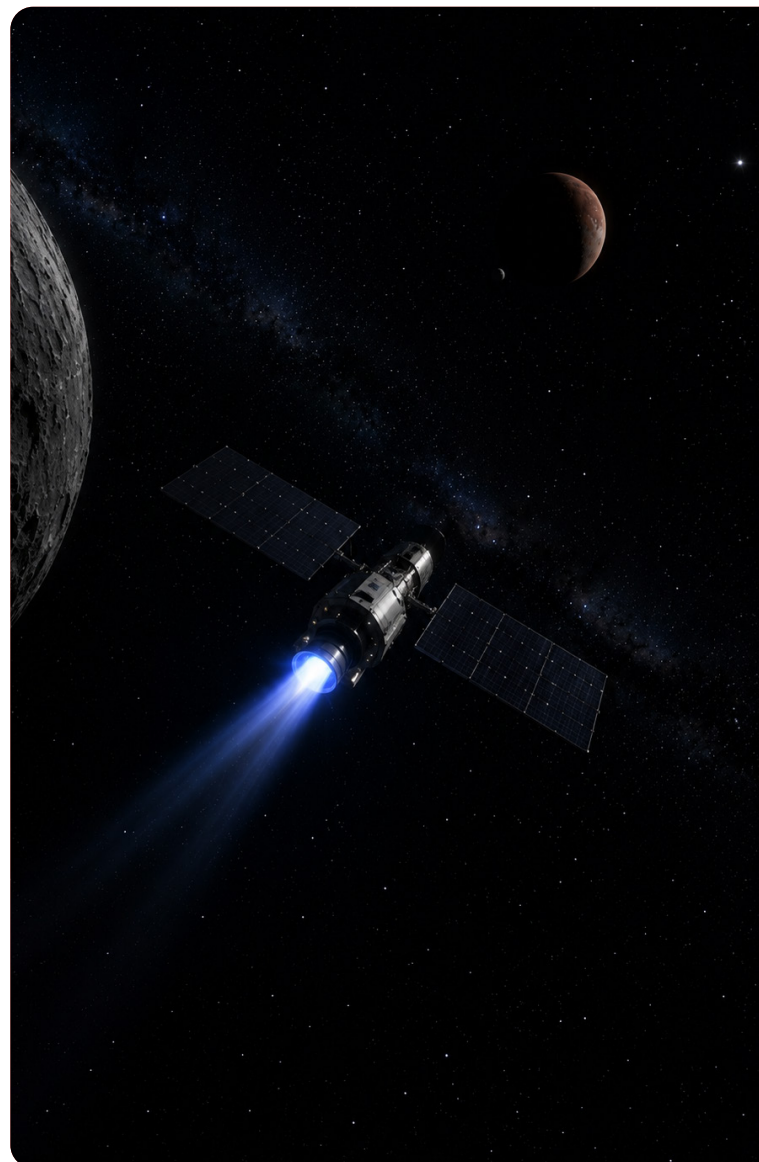


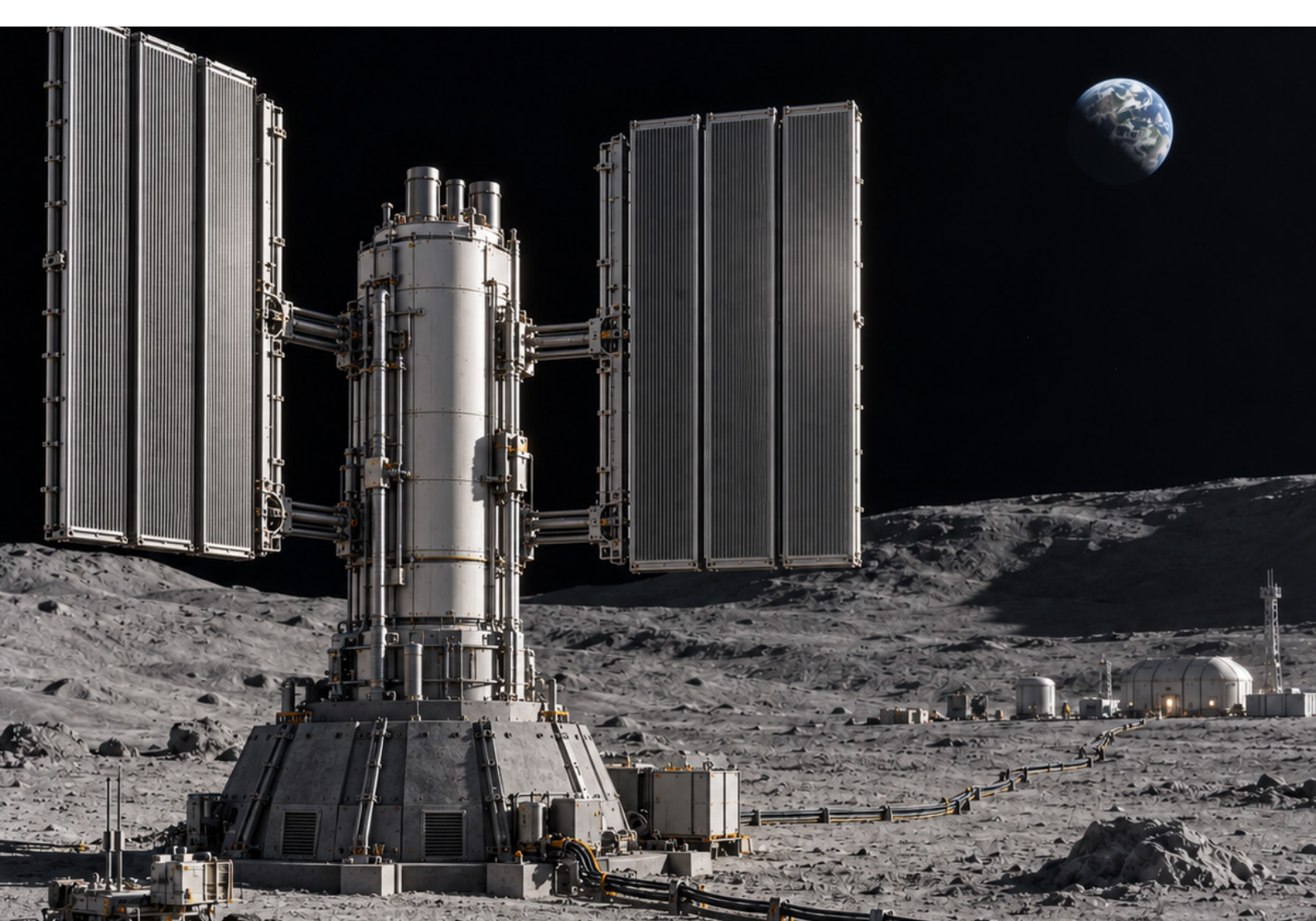
Table 11: Indicative Maturity of Advanced Propulsion and Space Power Systems

Technology Family	Stage of Adoption	TRL	MRL	Mkt-RL	Commercial Solution	Illustrative Case
Conventional Chemical Propulsion for Launch and Spacecraft Maneuvering	Mature and operational	9	8–9	8–9	Yes	Core technology for launch vehicles, orbit insertion, spacecraft maneuvering, and attitude or trajectory control. Current innovation focuses on reusability, improved engine performance, cost reduction, and safer or more accessible propellant options.
Green and Lower Toxicity Spacecraft Propulsion	Demonstrated with selective market uptake	7–8	6–7	5–6	Yes, niche	Relevant for safer handling, lower ground-processing burden, smallsat missions, and operators seeking alternatives to high-toxicity legacy propellants. Adoption depends on flight heritage, storage stability, supplier scale, performance, and compatibility with mission requirements.
EP Systems	Operational and scaling commercially	8–9	7–8	7–8	Yes	Hall, ion, plasma, and smallsat EP systems are increasingly used for station-keeping, orbit raising, and in-space mobility. ESA's BepiColombo mission⁵⁷ demonstrated high-performance solar EP for interplanetary transfer. At the same time, suppliers such as ThrustMe, ENPULSION, and Exotrail reflect growing commercial availability in the smallsat and satellite mobility market.
High-Power Solar EP	Qualification and program-level adoption	7–8	6–7	5–6	Emerging	Relevant for exploration, cislunar logistics, orbital transfer vehicles, and high-power spacecraft. NASA's Advanced Electric Propulsion System and Gateway Power and Propulsion Element ⁵⁸ illustrate the move towards higher-power electric propulsion architectures.

Technology Family	Stage of Adoption	TRL	MRL	Mkt-RL	Commercial Solution	Illustrative Case
Radioisotope Power Systems	Operationally mature for specialized institutional missions	9	7–8	3–4	Limited, mostly institutional	Used for long-duration missions where solar power is insufficient or impractical. Adoption remains constrained by isotope availability, nuclear-material controls, safety requirements, and cost.
Fission Surface Power and Nuclear Power Systems	Development and demonstration planning	4–6	3–4	2–3	Not yet routine commercial service	Relevant for lunar surface power, deep-space infrastructure, and operations in environments where solar power is constrained. NASA and the US Department of Energy ⁵⁹ work on fission surface power illustrates institutional momentum toward lunar power systems.
NTP and NEP	R&D and program-level demonstration interest	3–6	2–4	2–3	No	For NTP: Relevant for high-energy deep-space transfer and potentially faster cislunar missions. Maturity depends on high-temperature fuel elements, hydrogen compatibility, reactor control, cryogenic fuel management, testing infrastructure, safety assurance, regulatory approval, and sustained program support. Progress has also been constrained by inconsistent program continuity and funding, including the termination of the DRACO flight-demonstration effort in 2025.⁶⁰ For NEP: Relevant for long-duration deep-space mobility and high-power missions. Maturity depends on fission power sources, efficient power conversion, lightweight heat rejection, high-power electric thrusters, and integrated reactor-power-propulsion validation.
Deployable High-Power Solar Arrays	Mature and expanding	8–9	8	7–8	Yes	Relevant for high-power satellites, solar EP, exploration spacecraft, and surface or infrastructure applications. Redwire's ROSA/i-ROSA ⁶¹ technology illustrates the expanding role of deployable solar arrays across LEO, GEO, deep space, ISS, and exploration applications such as NASA's DART mission.

Technology Family	Stage of Adoption	TRL	MRL	Mkt-RL	Commercial Solution	Illustrative Case
Energy Storage and Power Management & Distribution	Mature and evolving for higher power demand	8–9	7–8	7–8	Yes	Batteries, power-conditioning units, power electronics, and power management and distribution systems are widely used. Future needs include higher energy density, degradation resistance, thermal resilience, lunar-night survival, and support for high-power payloads and electric propulsion.

Overall, the maturity profile shows a cluster with strong near-term deployment potential, but uneven readiness across its most transformative technologies. Established propulsion and power systems are already supporting commercial and institutional missions. In contrast, higher-impact architectures such as high-power electric propulsion, nuclear propulsion, nuclear power, and long-duration energy storage remain constrained by integration complexity, thermal limits, qualification requirements, safety assurance, and uncertain demand. These gaps define the main technical and operational barriers that must be addressed before advanced propulsion and space power systems can scale from proven capabilities to broader mission infrastructure.



2.3.3

Key Technical and Operational Barriers

The development of advanced propulsion and space power systems is constrained by a set of interconnected barriers that shape the pathway from performance improvement to operational deployment. These barriers emerge across system design, environmental survivability, testing and qualification, supply-chain resilience, and regulatory acceptance. Together, they create a compounding effect in which improvements in one subsystem can introduce new constraints on mass, power, thermal management, integration complexity, or qualification cost.

Workshop findings and survey responses point to five interrelated barriers that define this landscape. Higher-performance propulsion often requires greater power availability, which increases thermal-management requirements and system mass. More capable power systems can enable longer and more demanding missions, but must survive radiation, thermal cycling, degradation, and extended operational lifetimes. Limited testing infrastructure impedes qualification, slows the build-up of flight heritage, and raises the cost and risk of adoption.

1. Mass, Power, Efficiency, and Thermal Trade-offs

Propulsion and power systems sit at the core of spacecraft mass and energy budgets. Higher thrust, higher energy density, longer mission duration, and greater payload performance often require additional mass, volume, power-processing capacity, heat rejection, and system complexity. This creates a persistent design challenge in which gains in one performance dimension can lead to penalties elsewhere.

These trade-offs are especially important for higher-power electric propulsion, nuclear electric propulsion, lunar surface power, and deep-space power architectures. For high-power electric propulsion, the primary challenge is balancing thruster

performance with the spacecraft's ability to generate, process, distribute, and reject heat associated with sustained electrical power. For nuclear electric propulsion, performance is further constrained by thermal-to-electric conversion efficiency and radiator mass. Nuclear thermal and high-energy chemical systems impose additional requirements for cryogenic fuel management, insulation, and active cooling, thereby increasing operational complexity and system mass. Consequently, the core engineering challenge is to optimize mass, power, efficiency, thermal management, and performance while keeping development and qualification costs within mission-relevant limits.

2. Environmental Survivability and Long-Duration Reliability

Advanced propulsion and space power systems must operate in environments that degrade materials, electronics, fluids, coatings, and moving parts over time. Radiation, vacuum, thermal cycling, plasma interactions, micrometeoroid exposure, and, for lunar missions, abrasive dust impose strict requirements on system durability. These conditions affect solar cells, batteries, power electronics, propellant-storage systems, valves, seals, thermal coatings, fuel elements, and high-temperature materials.

The challenge is ensuring that components can both function in space and maintain performance over mission-relevant durations. Thruster lifetime, cathode and grid degradation, battery cycling, solar-array degradation, cryogenic boil-off, valve reliability, and heat rejection performance can all become gating factors for adoption. This is particularly important for cislunar, lunar surface, and deep-space missions, where maintenance access is limited and failure tolerance is low.

3. Testing, Qualification, and Flight Heritage

The transition from prototype to flight-ready propulsion or power systems depends on expensive, specialized testing infrastructure. These technologies require thermal-vacuum chambers, plume-interaction facilities, radiation testing, vibration and shock testing, high-power electrical testing, long-duration

thruster endurance testing, cryogenic-fluid validation, and, in the case of NTP, effluent gas scrubbing and safety assessment. Limited access to such facilities increases development costs and extends qualification timelines, particularly when new facilities must be built from scratch. This constraint was reinforced by the survey and workshop discussions, which identified limited ground-testing capabilities, lengthy qualification timelines, and high testing costs as core barriers to maturity.

This creates a bottleneck in the path from technical demonstration to operational maturity. A system may perform well in laboratory or subsystem tests yet still lack the flight heritage required for commercial adoption, institutional procurement, or insurance confidence. The challenge is more acute for high-power electric propulsion, long-duration cryogenic storage, nuclear propulsion, fission surface power, and advanced power systems, where realistic end-to-end testing is costly, time-consuming, and difficult to replicate on the ground.

4. Supply-Chain Resilience and Strategic Dependency

Advanced propulsion and space power systems depend on specialized suppliers, qualified materials, precision manufacturing, and high-reliability components. Valves, feed systems, batteries, power electronics, solar-array materials, high-temperature materials, radiation-tolerant components, power-processing units, and cryogenic hardware often rely on narrow supplier bases and long procurement timelines. Production scaling is difficult when demand is fragmented, volumes are low, and qualification requirements are strict.

This barrier has both commercial and strategic dimensions. Export controls, sensitive-technology restrictions, technology-transfer limitations, and supplier concentration can constrain access to critical inputs, particularly for strategic and high-assurance missions and for emerging space economies seeking domestic or regional capability. As a result, supply-chain fragility can slow adoption even where the underlying technology is technically mature.

5. Policy, Safety, and Public Acceptance for Space Nuclear Technologies

Nuclear power and nuclear propulsion face an additional layer of maturity constraints because technical readiness must be matched by safety assurance, regulatory approval, launch authorization, institutional confidence, and public acceptance. Radioisotope power systems, fission surface power, nuclear thermal propulsion, and NEP each require credible risk-management frameworks across development, launch, operation, and end-of-life handling. These requirements make space nuclear technologies particularly sensitive to policy continuity, funding stability, and public trust.

Beyond technical feasibility, space nuclear technologies must demonstrate a safety case that is credible to regulators, governments, mission operators, insurers, and the public. This includes clear approval pathways, sustained institutional commitment, and security frameworks for handling, launch, operation, and end-of-life management of nuclear material. Survey and workshop discussions reinforced that nuclear materials requiring higher levels of enrichment introduce additional security and non-proliferation concerns. Clear governance and robust assurance mechanisms can accelerate the transition of nuclear propulsion and power from program-level development to more routine mission use.

These barriers show that maturity in advanced propulsion and space power systems depends on more than improving thrust, efficiency, or energy density. The decisive challenge is system-level readiness: the ability to integrate, test, qualify, regulate, and scale technologies that operate under severe environmental, thermal, safety, and supply-chain constraints. Addressing these barriers will determine how quickly the cluster can move from mature point solutions and selective demonstrations to broader deployment across orbital, cislunar, lunar, and deep-space missions.

2.3.4

Market Potential and Strategic Relevance

Advanced propulsion and space power systems have strong market potential because they are foundational to mission mobility, endurance, and operational flexibility. Their relevance extends across launch vehicles, satellites, transfer vehicles, lunar landers, cislunar transport systems, surface power assets, and deep-space missions. As spacecraft become more maneuverable, power-intensive, autonomous, and long-lived, demand will grow for propulsion and power technologies that can extend mission life, improve responsiveness, support higher payload performance, and enable operations beyond traditional Earth-orbit missions.

Public market estimates point to strong growth, although figures vary by scope and market definition. MarketandMarkets⁶² estimates the broader space propulsion market at \$10.2 billion in 2024, growing to \$20.0 billion by 2030, with an 11.9% CAGR. Within that broader category, it estimates the satellite propulsion market at \$2.6 billion in 2024, growing to \$5.2 billion by 2030 at a 12.2% CAGR.⁶³ Grand View Research⁶⁴ estimates the satellite propulsion system market at \$11.1 billion in 2024, growing to \$23.2 billion by 2030 at a CAGR of 13.6%. Although the Grand View satellite propulsion estimate is more than four times larger in absolute market size, the projected growth rates are relatively close, differing by only 1.4%. This suggests directional alignment on growth, while also showing that market sizing is highly sensitive to whether the studies include components, systems, platforms, services, end-use categories, or broader value-chain elements.

The near-term commercial opportunity is concentrated on technologies that already support operational missions. EP, conventional chemical propulsion, deployable solar arrays, batteries, power electronics, and power management and distribution systems are increasingly tied to satellite maneuverability, station-keeping,

orbit raising, mission-life extension, and higher payload duty cycles. Market growth is therefore driven by both new mission types and rising performance requirements in existing satellite and launch markets.

The medium-term opportunity lies in systems that expand mission flexibility and reduce operational constraints. Green and lower-toxicity propulsion can reduce ground-handling burdens and support smallsat adoption, while high-power solar electric propulsion can enable orbital transfer vehicles, exploration architectures, and cislunar logistics. Deployable high-power solar arrays, energy storage, and power management systems will also become more important as payloads demand more energy for communications, onboard processing, sensing, autonomy, and sustained operations.

The longer-term strategic opportunity is linked to nuclear propulsion and nuclear power systems. Nuclear thermal propulsion could improve high-energy transfer options, while nuclear electric propulsion and fission surface power could support deep-space mobility, lunar surface infrastructure, and missions where solar power is limited or unreliable. These technologies remain at lower maturity levels, but their strategic relevance is high because they could expand the practical duration, efficiency, and autonomy of future space activities.

Strategically, this cluster matters because propulsion and power systems sit close to the core of mission independence. Actors with reliable access to advanced propulsion, high power-density systems, high energy-density storage, power electronics, deployable solar systems, cryogenic fuel management, and nuclear power capabilities will have greater control over mission design, maneuverability, endurance, and participation in cislunar and deep-space architectures. Conversely, dependence on external suppliers for these technologies can create bottlenecks for resilient and strategically important missions, and emerging space economies seeking to build domestic or regional capabilities.

Overall, the market opportunity is strongest where technical maturity aligns with clear operational demand. Mature propulsion

and power systems are already embedded in operational missions, while emerging architectures could expand the geography, duration, and responsiveness of future space activity. The pace of adoption will depend on whether these technologies can move from bespoke applications to institutional demonstrations to qualified, scalable, and economically viable deployment pathways.

2.3.5

Cross-Cutting Applications

Advanced propulsion and space power systems have strong cross-sector relevance because many of their core challenges are shared with terrestrial industries

operating under extreme performance, reliability, safety, and energy constraints. These include energy systems, electric mobility, aviation, hydrogen and cryogenic infrastructure, nuclear engineering, advanced manufacturing, semiconductors, mining, and critical infrastructure. The relationship is two-directional: terrestrial sectors can accelerate space technology maturation through proven methods, materials, power systems, and manufacturing processes, while space applications can generate spin-offs for high-reliability energy, mobility, remote operations, and harsh-environment systems on Earth.

Table 12 summarizes the main cross-sector pathways in which terrestrial capabilities can accelerate the maturation of advanced propulsion and space power systems, and in which space-driven requirements may generate broader industrial value.

Table 12: Cross-Cutting Applications of Advanced Propulsion and Space Power Systems

Cross-Cutting Area	Terrestrial Capability (Spin-In)	Space Application	Terrestrial Benefits (Spin-Off)
Energy Systems and Microgrids	Terrestrial microgrid design, battery management, smart grid controls, renewable integration, and resilient power planning can support space power architectures	Lunar surface power, spacecraft power management, high-power payloads, ISRU plants, habitats, surface mobility, and distributed cislunar infrastructure	More resilient terrestrial microgrids, desert infrastructure, remote energy systems, and disaster response power solutions
Electric Mobility and Power Electronics	Electric vehicles, aviation electrification, inverters, power conversion, battery management, and high-efficiency electronics can support spacecraft power and propulsion systems	Higher-density energy storage, power conditioning, EP, high-power payloads, and onboard energy management	Improved high-reliability batteries, thermal systems, and power electronics for aviation, critical infrastructure, transport, and remote operations

Cross-Cutting Area	Terrestrial Capability (Spin-In)	Space Application	Terrestrial Benefits (Spin-Off)
Hydrogen, Cryogenics and Fluid Systems	Liquid natural gas, hydrogen, chemical processing, aerospace fueling, and industrial cryogenic expertise can support propellant storage and handling	Cryogenic propellant management, nuclear thermal propulsion, high-energy chemical propulsion, in-orbit refueling, lunar logistics, launch systems, and deep-space transfer architectures	Better hydrogen storage, thermal insulation, cryogenic handling, boil-off management, and safety systems for clean-energy and industrial infrastructure
Advanced Materials and Thermal Management	Aviation, turbine, nuclear, automotive, semiconductor, and energy industries contribute to the development of high-temperature materials, coatings, composites, insulation, and heat-management solutions	Chemical engines, RDREs, EP components, nuclear propulsion, re-entry systems, power electronics, lunar hardware, radiators, and deep-space systems	Stronger materials and heat management solutions for harsh environments, industrial heat systems, semiconductors, aerospace, and energy assets
Advanced Manufacturing and Qualification	Additive manufacturing, precision machining, digital twins, non-destructive inspection, quality assurance, and high-reliability production methods can reduce development and qualification burdens	Thrusters, valves, injectors, combustion chambers, lightweight structures, power and thermal components, and customized mission hardware	Higher-quality industrial manufacturing, predictive maintenance, inspection methods, and qualification approaches for safety-critical sectors
Mining and Remote Operations	Mining automation, ruggedized machinery, dust management systems, remote maintenance, and off-grid power expertise can support lunar and planetary surface operations	ISRU, lunar mobility, excavation, regolith handling, surface power systems, and robotic maintenance	Improved autonomous mining, remote equipment maintenance, off-grid operations, and hazardous environment industrial systems
Nuclear Engineering and Safety Governance	Nuclear licensing, fuel handling, safety cases, reactor engineering, emergency planning, and public-risk communication can inform space nuclear power and propulsion	Radioisotope power systems, fission surface power, NEP, and nuclear thermal propulsion	Improved safety assurance, public-risk governance, and regulatory approaches for advanced nuclear, remote power, and higher-reliability energy systems
Responsive Operations	Logistics, resilient communications, secure electronics, and rapid deployment can support responsive space capabilities	Agile constellations, maneuverable spacecraft, tactical ISR, rapid repositioning, and con-tested-space resilience	Stronger industrial capacity, resilient logistics, and secure infrastructure operations

Progress toward maturity in this cluster will not depend solely on further advances within the space sector. Terrestrial industries already hold relevant capabilities in power management, cryogenics, hydrogen handling, nuclear safety, high-temperature materials, advanced manufacturing, and remote operations. The opportunity is to translate these capabilities into space-qualified systems while allowing space-driven requirements to generate stronger technologies for resilient energy, mobility, and harsh-environment operations on Earth.

2.3.6

Time to Maturity

Time-to-maturity for advanced propulsion and space power systems varies significantly across technology families, mission environments, safety requirements, and levels of commercial demand. Near-term adoption is concentrated on technologies with existing flight heritage, established suppliers, and clear operational use cases, while longer timelines apply to high-power, cryogenic, nuclear, and deep-space architectures. The pace of maturity will depend on whether the sector can move from component-level performance improvements to qualified, integrated systems that can operate reliably across orbital, cislunar, lunar, and deep-space environments.

3–5 years: Near-term maturity is most likely in EP for satellites, improvements to conventional chemical propulsion, green and lower-toxicity propulsion, deployable solar arrays, batteries, power electronics, and power management and distribution systems. These technologies already benefit from commercial providers, flight heritage, and clear mission demand for station-keeping, orbit raising, maneuverability, mission-life extension, and higher payload duty cycles. Continued maturity during this period will be driven by cost reduction, supplier scale, improved qualification pathways, and broader integration into satellite and spacecraft platforms.

5–8 years: Medium-term maturity is likely in high-power solar electric propulsion, advanced energy storage, higher-capacity deployable solar arrays, integrated propulsion-power architectures, and selected cryogenic propellant management capabilities. These technologies require

greater system-level validation because their performance depends on power availability, thermal management, storage stability, and mission-level integration. NASA's high-power Advanced Electric Propulsion System (AEPS) program and the growing base of commercial electric propulsion suppliers illustrate the shift from technology development toward mission incorporation. Adoption during this period will depend on demonstration missions, shared testing infrastructure, government anchor demand, and clear procurement pathways supporting exploration, satellite mobility, and early cislunar mission architectures.

8–15+ years: Longer timelines are expected for nuclear thermal propulsion, nuclear electric propulsion, fission surface power, large-scale lunar power systems, and high power-density architectures for deep-space infrastructure. These technologies face additional requirements related to nuclear safety cases, launch approval, public acceptance, nuclear material security, thermal-to-electric conversion, radiator performance, cryogenic fuel management, and sustained institutional funding. NASA's target for a 40-kW-class lunar fission surface power system⁶⁵ by the early 2030s illustrates this longer development horizon. Their maturity will depend less on isolated technical demonstrations and more on credible mission architectures, regulatory confidence, supply-chain readiness, and long-term anchor demand from cislunar, lunar, Mars-class, and deep-space programs.

2.3.7

Acceleration Measures

Acceleration of maturity depends on coordinated, technical, industrial, regulatory, and market actions, including:

1. Anchor Demand and Mission-Linked Procurement

Government users and large institutional buyers should create credible demand signals through mission-linked procurement, co-funded demonstrations, early adoption contracts, and national exploration programs requiring advanced propulsion and space power capabilities. This is especially important for high-power electric propulsion, space nuclear technologies, fission surface power, and long-duration power architectures, where commercial demand alone may not justify early investment. Demand signals should be tied to mission outcomes, such as higher mobility, longer mission life, lunar surface operations, or deep-space endurance, rather than generic technology development.

2. System-Level Demonstrations and Flight Heritage

The sector needs more demonstrations that validate integrated propulsion and power performance under realistic mission conditions. Priority areas include high-power electric propulsion, integrated power-processing units, higher-power deployable solar arrays, advanced energy storage, cryogenic fuel management, and nuclear power or propulsion pathfinders. The objective is not only to prove individual components, but also to validate full operating architectures across power generation, storage, conversion, propulsion, heat rejection, and mission operations.

3. Shared Qualification and Testing Infrastructure

Maturity will require improved access to thermal-vacuum testing, plume-interaction facilities, radiation testing, vibration and shock testing, high-power electrical

testing, long-duration thruster endurance testing, cryogenic-fluid validation, materials degradation testing, and nuclear safety assessment capabilities. Shared or nationally coordinated testing infrastructure can reduce duplication, lower barriers for emerging suppliers, shorten qualification timelines, and improve confidence among operators, regulators, insurers, and investors. This is particularly important for technologies that cannot build market trust without long-duration validation and flight heritage.

4. Standardized Interfaces and Serviceable Spacecraft Design

The sector should move toward clearer standards for power interfaces, propulsion integration, power-processing units, propellant storage, safety margins, testing documentation, and qualification evidence. Standardization can reduce integration costs, improve supplier scalability, and help customers compare technologies across providers. For propulsion and power systems, this is especially important because bespoke integration increases mission cost and slows adoption even when the underlying technology is technically mature.

5. Supply-Chain Resilience and Industrial Scale-Up

National and regional strategies should identify bottlenecks in propulsion components, valves, feed systems, batteries, solar cells, high-temperature materials, power electronics, power-processing units, cryogenics hardware, radiators, and test facilities. Supply-chain resilience is essential for national capability, exploration, and long-duration missions because many of these technologies depend on specialized suppliers, export-controlled components, and low-volume production. Industrial scale-up will require supplier diversification, qualified manufacturing capacity, repeatable production, and stronger links between space demand and adjacent sectors such as energy, aviation, nuclear, hydrogen, automotive, semiconductors, and advanced manufacturing.

6. Clear Policy Pathways for Nuclear and High-Power Systems

Nuclear propulsion and nuclear power systems require predictable approval pathways that cover safety assurance, launch authorization, nuclear material security, environmental reviews, liability, public-risk communication, and end-of-life management. High-power systems also require clearer treatment of multi-application sensitivities, export controls, confidence measures, and mission safety requirements. Predictable governance and streamlined approval processes can accelerate progress and advance these strategically important technologies.

7. Cross-Sector Partnerships and Spin-in Pathways

The energy, nuclear, hydrogen, mining, aviation, automotive, semiconductor, and advanced manufacturing sectors should be treated as strategic partners rather than peripheral contributors. These industries already hold relevant capabilities and expertise in many intersecting areas. Structured spin-in partnerships can reduce costs, shorten qualification cycles, improve industrial readiness, and expand terrestrial value.



2.4

In-Situ Resource Utilization & Space Resources

ISRU could reduce launch mass, cost, and dependence on Earth by supplying essential resources for sustained operations beyond Earth.

2.4.1

Definition

In-Situ Resource Utilization (ISRU) refers to the discovery, extraction, processing, storage, and operational use of resources found beyond Earth. Space resources include lunar regolith, water ice, volatiles, oxygen-bearing minerals, metals, asteroid materials, and constituents of the Martian atmosphere. Rather than transporting all mission resources from Earth, ISRU seeks to convert locally available materials into products such as oxygen, water, propellant, shielding, construction materials, and industrial feedstocks that support sustained space operations.

ISRU is best understood as an integrated resource value chain with four interconnected stages:

- 1. Resource discovery and characterization:** identifying, mapping, and assessing the location, accessibility, composition, distribution, quantity, and quality of resources.
- 2. Extraction:** recovering materials through drilling, excavation, regolith handling, or volatile capture.
- 3. Processing and storage:** converting raw materials into usable products through

beneficiation, chemical processing, electrolysis, purification, liquefaction, and storage.

4. Operational use: applying locally produced resources to life support, propulsion, radiation shielding, construction, energy infrastructure, and surface or cislunar logistics.

Although these stages collectively comprise the ISRU value chain from resource discovery to utilization, they differ significantly in technological maturity, operational risk, system requirements, and market readiness. Progress in one stage does not imply maturity across the entire value chain, so each stage must be assessed independently and as part of an integrated end-to-end system.

2.4.2

Maturity Level

ISRU's overall maturity is low, with significant variation across the resource value chain. Resource prospecting, mapping, drilling technologies, volatile detection, laboratory-scale resource processing, analogue testing, and early robotic excavation systems continue to advance. However, reliable end-to-end extraction, processing, storage, distribution, and operational use of local resources have not been demonstrated at

sustained operational scale on the Moon, asteroids, or Mars.

As shown in Figure 6, the survey reflects the gap between ISRU's strategic potential and its current readiness. ISRU and Space Resources score 2.67/5 for technology readiness, 4.33/5 for market potential, 2.33/5 for policy fit, 3.00/5 for time to maturity, and 4.33/5 for cross-cutting potential. The average across all five assessment dimensions is 3.33/5. These findings suggest that ISRU is recognized as strategically important, commercially promising over the longer term, and highly cross-sectoral, while its technical maturity, governance frameworks, and pathways to commercial deployment remain comparatively underdeveloped. The low policy-fit score reflects ongoing uncertainty around resource rights, liability, operational governance, and diverging national and international regulatory approaches.

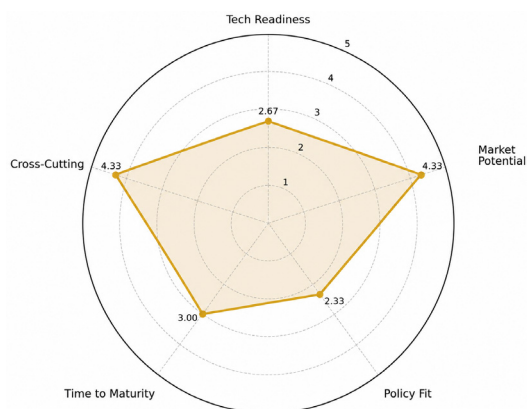


Figure 6: Maturity Level for ISRU and Space Resources, CSF Survey Results, 2025

The maturity assessment in Table 13 examines readiness at each stage of the value chain rather than treating individual demonstrations as evidence of overall ISRU maturity. Prospecting, drilling, volatile detection, and laboratory-scale processing have progressed through terrestrial testing and limited mission demonstrations. However, integration of these capabilities into reliable systems for extraction, processing, storage, distribution, and operational use remains at an early stage.

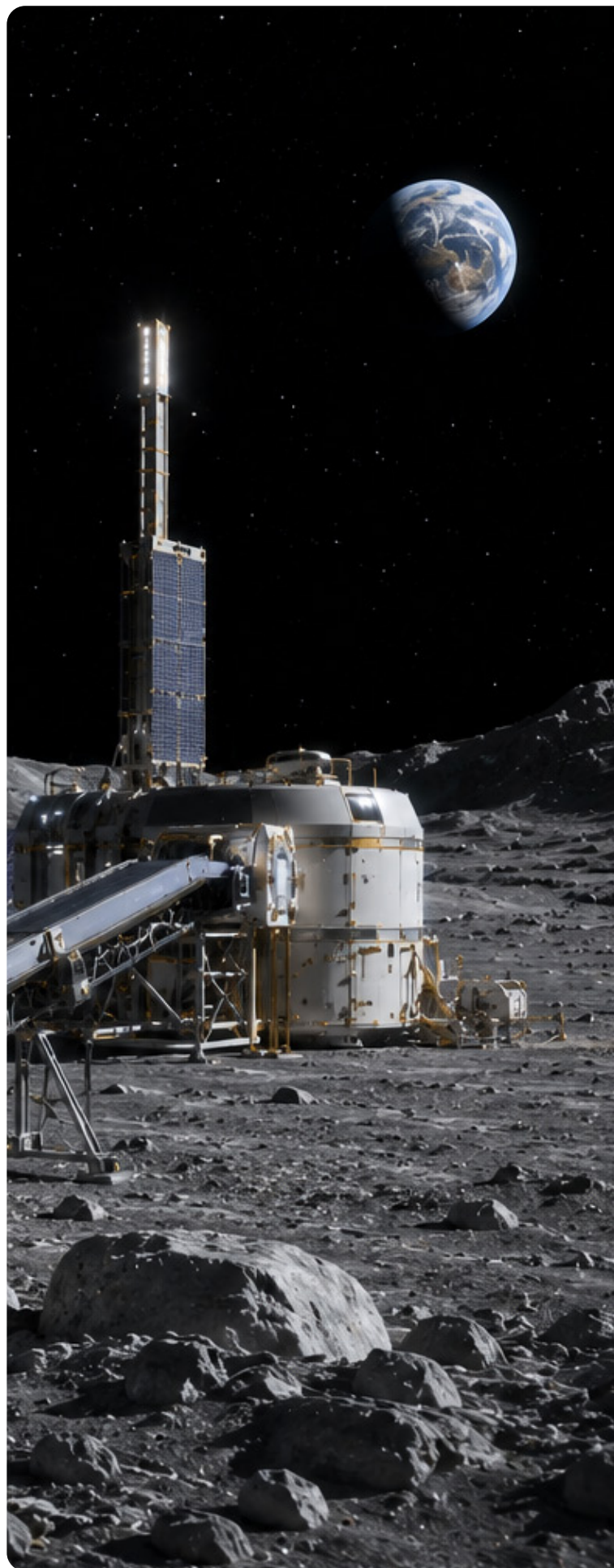


Table 13: Indicative Maturity Assessment Across the ISRU and Space Resources Value Chain

Capability	Stage of Adoption	TRL	MRL	Mkt-RL	Commercial Solution	Illustrative Case
Resource prospecting and mapping	Orbital mapping is established, while high-resolution surface characterization and validation remain emerging	5–8	5–6	4–5	Commercial delivery and sensing capabilities exist, but dedicated resource-data services remain limited	Orbital missions have identified potential resource locations, while CLPS provides a pathway for delivering surface prospecting payloads. PRIME-1 demonstrated partial hardware operation on the lunar surface, but did not complete its intended drilling and volatile-analysis objectives. ⁶⁶
Lunar drilling and subsurface sampling	Partial lunar hardware demonstration; subsurface sampling remains unvalidated	5–6	4–5	3–4	Emerging through suppliers	TRIDENT deployed and completed its commanded range-of-motion and hammering tests, but the lander's final orientation prevented the drill from reaching the lunar surface and completing the planned drilling and coordinated volatile-analysis sequence. ⁶⁷
Volatile detection and water-ice prospecting	Demonstration stage	5–7	4–5	3–5	Mostly institutional	VIPER is intended to search for volatile resources, such as ice, at the south lunar pole. NASA awarded Blue Origin a CLPS task order with an option to deliver VIPER in late 2027 using a Blue Moon MK1 lander. ⁶⁸
Regolith excavation and handling	Prototype and analogue testing	4–6	3–5	3–5	Emerging	NASA, its contractors, and industry partners have developed and tested autonomous excavation and regolith-handling prototypes in terrestrial and simulated ⁶⁹ lunar environments.
Oxygen extraction from lunar regolith	Laboratory and relevant-environment testing	4–6	3–5	3–4	Not routine	Multiple processes, including carbothermal reduction and molten regolith electrolysis, have produced oxygen from lunar simulants in laboratory or relevant environments. No sustained lunar-surface production system has yet been demonstrated. ⁷⁰

Capability	Stage of Adoption	TRL	MRL	Mkt-RL	Commercial Solution	Illustrative Case
Water extraction from lunar polar volatiles	Laboratory development and mission preparation	4–6	3–4	3–4	Not routine	Technologies for heating, capturing, purifying, and processing water from icy regolith are under development, but extraction from verified lunar polar deposits has not yet been demonstrated.
Propellant production from local resources	Conceptual to early integrated ground demonstration	3–5	2–4	3–4	No routine service	Ground demonstrations have integrated elements of extraction, processing, electrolysis, and storage. ⁷¹ However, lunar production, liquefaction, storage, transfer, and use of locally sourced propellant remain undemonstrated. ⁷²
Regolith-based construction and surface infrastructure	Analogue testing, component development, and early R&D	3–5	2–4	3–4	Emerging, not operational	Terrestrial demonstrations have tested regolith sintering, additive construction, landing-pad concepts, and shielding applications. These systems have not yet been validated at operational scale on the Moon. ⁷³
Asteroid prospecting and extraction	Concept development and limited precursor exploration	3–5	2–3	2–4	Very early	Hayabusa and Hayabusa2 demonstrated asteroid sampling and sample return. ⁷⁴ Hayabusa2 collected surface and subsurface material from Ryugu and returned 5.4 grams to Earth, but did not demonstrate industrial extraction or utilization.

Operational ISRU depends on the integration and reliable performance of every stage of the resource value chain. Current exploration programs are steadily advancing individual capabilities through technology demonstrations that help reduce technical uncertainty, although no mission has yet demonstrated the complete end-to-end resource chain beyond Earth. ISRU therefore remains a long-horizon strategic capability, with its constituent technologies progressing at different rates. Realizing its full operational potential will require clearer governance frameworks, integrated technology demonstrations, credible business models and procurement pathways, effective risk allocation, and stronger international coordination.

2.4.3

Key Technical and Operational Barriers

ISRU remains a long-term capability because every stage of the resource value chain must operate reliably in the demanding environments of space. Progress therefore depends not on a single technological breakthrough but on overcoming a combination of technical, economic, legal, and operational constraints. The principal barriers are systemic and mutually reinforcing.

1. Governance uncertainty

The absence of widely aligned rules for space resource activities creates uncertainty over how ISRU missions will be authorized, supervised, coordinated, and held accountable. Key unresolved issues include resource rights, priority of access, non-interference, liability, environmental protection, safety measures,⁷⁵ and responsibility for damage or contamination. The Moon Agreement,⁷⁶ the Artemis Accords,⁷⁷ the International Lunar Research Station⁷⁸ (ILRS) partnership framework, and national resource legislation reflect different legal and policy approaches, although they do not have the same status or scope. This lack of alignment increases regulatory and commercial risk, complicates cross-border partnerships, and makes long-term ISRU investment and operations more difficult to plan.

2. Technology immaturity

Although individual ISRU technologies continue to advance, the overall resource value chain remains technically immature. Progress has been made in prospecting, drilling, volatile detection, laboratory-scale processing, and robotic excavation. However, reliable end-to-end ISRU, from resource extraction through processing, storage, and operational use, has not been demonstrated beyond Earth. Missions such as NASA's Polar Resources Ice Mining Experiment (PRIME-1) also highlighted the difficulty of delivering and operating ISRU hardware in the lunar

environment. As a result, substantial flight validation remains necessary before ISRU systems can support sustained missions.

3. Economic ambiguity

The commercial case for ISRU remains uncertain because future demand, pricing mechanisms, and investment returns are not yet well established. Current activity is largely supported by public exploration programs rather than by self-sustaining commercial markets. Workshop discussions highlighted limited anchor customers, uncertain revenue models, high infrastructure costs, and long investment horizons as significant barriers to private investment. Until credible procurement pathways, reliable demand signals, and viable customer markets emerge, commercial deployment is likely to remain constrained.

4. System complexity

ISRU presents a significant system-integration challenge. Operational capability requires prospecting, excavation, material handling, chemical processing, power generation, thermal management, autonomous operations, storage, logistics, and delivery to end users to function within one architecture. Failure at any stage can compromise the entire resource chain. Integration, reliability, and interoperability are therefore as important as the performance of individual technologies.

5. Risk allocation and insurability

The technical, operational, and commercial risks associated with ISRU remain difficult to allocate and insure. Uncertainty about resource quality, system performance, contamination, damage to third-party assets, liability, and investment recovery complicates both insurance provision and project financing. The absence of established operational standards and sufficient performance data further limits insurers' ability to assess risk, price coverage, and

determine responsibility when failures occur. This reduces investor confidence in large-scale ISRU activities.

6. Geopolitical fragmentation

Parallel lunar infrastructure initiatives led by different international coalitions are increasingly shaping ISRU development. The US-led Artemis architecture and the China-Russia-led ILRS both stimulate investment, technology demonstrations, and long-term demand. However, they also risk creating divergent approaches to technical standards, interoperability, data sharing, safety measures, environmental protection, and operational coordination. Without greater convergence on these foundational principles, fragmented governance could raise costs, restrict interoperability, and slow the development of a broader ISRU ecosystem.

2.4.4
Market Potential and Strategic Relevance

ISRU remains a pre-commercial capability. The figures in Table 14 offer directional indicators of increasing investment and policy attention rather than evidence of established commercial markets or reliable forecasts of future revenue. Existing estimates apply different definitions and often combine space mining, lunar infrastructure, payload delivery, prospecting technologies, resource processing, and anticipated in-space resource services. They should therefore be interpreted individually and should not be directly compared or aggregated.

Table 14: Overview of Market Report Insights into ISRU and Space Resources

Source	Market Scope	Market Size and Growth	Strategic Implication
Grand View Research ⁷⁹	Space mining	\$1.90B (2024) - \$5.02B (2030), CAGR 17.6%	Indicates strong growth expectations but remains tied to early-stage exploration, prospecting, and investment assumptions
DataIntel ⁸⁰	ISRU market	\$2.80B (2025) - \$9.40B (2034) CAGR 14.4%	Associates future demand with lunar exploration programs, autonomous extraction, and resource-processing technologies
Fact.MR ⁸¹	Space mining	\$50.0M (2025) - \$1.06B (2036), CAGR 32.0%	Applies a much narrower market scope and illustrates the wide variation among published estimates

Near-term demand is likely to be driven primarily by public exploration architectures rather than independent resource markets. Initial opportunities are expected in lunar delivery services, prospecting payloads, resource mapping, drilling and excavation systems, volatile detection, resource-data services, and demonstration missions. These activities can validate individual elements of the ISRU value chain and reduce technical uncertainty, but they do not yet constitute a

functioning resource market. Longer-term commercial opportunities may develop around oxygen and water production, propellant production, construction materials, surface infrastructure, power systems, resource-processing, and logistics. Their emergence will depend on reliable transportation and surface infrastructure, sustained mission demand, clear governance arrangements, and anchor

customers capable of supporting early operations. These conditions must develop together; progress in resource technology alone will not create a scalable market.

The strategic importance of ISRU extends beyond forecast market revenues. By reducing the mass and volume transported from Earth, ISRU could lower logistics requirements, extend mission duration, improve operational autonomy, and support more scalable lunar and deep-space infrastructure. It is therefore best understood as an enabling capability for sustained operations rather than solely as a resource-extraction industry. The survey reinforces this view by identifying reduced dependence on Earth-based supply chains as its principal long-term value.

Public exploration architectures are already shaping the direction and pace of ISRU development. NASA's Artemis program, supported by Commercial Lunar Payload Services⁸² (CLPS), provides mission demand and recurring opportunities to deliver scientific and technology payloads to the lunar surface. CLPS functions primarily as a procurement and delivery mechanism, not as evidence of an established ISRU market. Missions such as PRIME-1 also demonstrate that progress depends not only on the readiness of ISRU hardware but also on reliable transportation, landing, deployment, and surface operations. Similarly, the ILRS provides a long-term, state-led pathway for lunar exploration, scientific activity, and infrastructure development. Its phased development could generate demand for resource characterization, surface mobility, construction, power, life-support, and local resource utilization. Artemis⁸³ and ILRS⁸⁴ therefore represent parallel infrastructure pathways that can anchor investment and create mission-linked demand for ISRU capabilities. However, they are structured differently and may develop distinct technical standards, partnership models, governance approaches, and operational practices. Neither pathway should be interpreted as evidence that reliable end-to-end ISRU has reached operational maturity.

Other national and joint missions complement these broader architectures by advancing specific elements of the ISRU

value chain. India and Japan are developing the Chandrayaan-5⁸⁵/LUPEX⁸⁶ mission to investigate the quantity, distribution, accessibility, and potential usability of water in the lunar polar region. Japan also contributes commercial lunar transportation capability through companies such as ispace,⁸⁷ strengthening the delivery and surface-access ecosystem needed for future demonstrations. Russia retains significant historical expertise and remains a participant in the ILRS pathway, although its near-term operational contribution remains uncertain.⁸⁸ Together, these activities broaden the international base of prospecting, drilling, mobility, transportation, and surface-operations capabilities that future ISRU systems will require.

Essentially, ISRU demand is likely to emerge first through publicly funded exploration architectures, joint missions, commercial lunar delivery contracts, and technology demonstrations. Broader commercial markets will develop only if these activities lead to greater technical maturity, reliable infrastructure, clearer governance, and sustained demand from credible customers.

2.4.5

Cross-Cutting Applications

ISRU received the highest cross-cutting potential score among the technologies assessed in the survey because many of its enabling capabilities already exist outside the space sector. Table 15 illustrates how adapting proven terrestrial capabilities to extraterrestrial environments can reduce technological risk and accelerate ISRU maturity. This relationship works in both directions: terrestrial industries can accelerate ISRU development, while ISRU demand can drive technologies and operating models with applications on Earth.

African institutions, industries, and research organizations could provide particularly relevant expertise in mining, geology,

remote operations, mineral economics, and resource governance.⁸⁹ These capabilities could support resource characterization, excavation, processing, risk assessment, and the development of responsible resource-management frameworks for future ISRU activities.

The demanding operational requirements of ISRU, including autonomous resource extraction, closed-loop resource management,

extreme-environment operations, and long-duration infrastructure, could also advance technologies with applications beyond the space sector. As these technologies mature, they may strengthen terrestrial capabilities in autonomous mining, off-grid energy systems, robotics for hazardous environments, circular construction, water recovery, risk modeling, and frontier infrastructure governance.

Table 15: Overview of the Cross-Sector Potential of ISRU and Space Resources

Cross-Cutting Area	Terrestrial Capability (Spin-In)	Space Application	Terrestrial Benefits (Spin-Off)
Mining and resource extraction	Mining engineering, autonomous drilling, excavation, beneficiation, ore characterization, and remote operations	Lunar drilling, regolith excavation, volatile extraction, asteroid prospecting, and resource mapping	Autonomous mining, safer remote operations, lower-impact extraction, and improved resource efficiency in hazardous terrestrial environments
Energy and power systems	Microgrids, solar thermal, nuclear energy systems, batteries, hydrogen, and power-management systems	Power for excavation and processing, electrolysis, thermal management, cryogenic storage, lunar-night survival, and surface infrastructure	Resilient microgrids, hydrogen systems, and off-grid power for remote communities
Robotics and autonomy	Mining, agricultural, and subsea robotics, and nuclear decommissioning	Autonomous prospecting, excavation, regolith handling, equipment maintenance, and construction	Better robotic operations for hazardous industrial sites, offshore energy, and disaster response
Construction and advanced materials	Civil engineering, additive manufacturing, ceramics, composites, sintering, and modular construction	Landing pads, roads, shielding, habitats, storage tanks, and spare parts from local materials	More resource-efficient construction, circular use of materials, and infrastructure suited to remote or extreme environments
Water, volatiles, and chemical processing	Water treatment, gas separation, cryogenics, chemical engineering, and industrial processing	Water extraction, oxygen/hydrogen production, fuel depots, life support, and industrial feedstocks	Improved water recovery, chemical processing, and closed-loop resource systems on Earth

Cross-Cutting Area	Terrestrial Capability (Spin-In)	Space Application	Terrestrial Benefits (Spin-Off)
Digital twins and simulation	Mining simulation, geotechnical modeling, industrial digital twins, and AI planning	Resource mapping, excavation planning, processing optimization, mission safety, and maintenance forecasting	Better predictive models for mining, energy, infrastructure, and supply chains
Legal, insurance, and financial engineering	Mining concessions, project finance, risk allocation, insurance modeling, and commodity contracting	Resource rights, safety measures, authorization, liability, customer contracts, and lunar service markets	New finance and insurance models for frontier infrastructure and autonomous industrial assets
International cooperation and shared infrastructure	International research stations, shared facilities, joint scientific programs, common standards, and multinational operating arrangements	Resource-data sharing, shared surface infrastructure, interoperability, coordinated lunar operations, and standards development across frameworks such as Artemis and ILRS	Stronger models for international cooperation in extreme-environment infrastructure and strategic technologies

Taken together, these interactions show that ISRU is not an isolated space capability but part of a broader innovation ecosystem. Terrestrial industries provide many of the technologies, operational experience, and governance models needed to accelerate ISRU development. Meanwhile, the challenges of operating beyond Earth create opportunities to advance technologies that can improve productivity, resilience, and sustainability in remote and resource-constrained environments on Earth. This two-way relationship extends the strategic value of ISRU beyond the space sector and helps explain its high cross-cutting potential score in the survey.

2.4.6

Time to Maturity

The maturity of ISRU will depend on sustained public investment, recurring opportunities for lunar missions and technology demonstrations, the progressive development of a governance framework, and the emergence of credible commercial

demand. Because these conditions remain uncertain, the following timeframes represent scenario-based maturity horizons rather than fixed predictions. Progress across the ISRU value chain is expected to be uneven, with prospecting and resource characterization likely to mature well before integrated resource production and sustained operational use.

Estimated Maturity Timelines:

3–5 years: Progress is most likely to occur in precursor capabilities that reduce technical uncertainty. These include resource prospecting, drilling demonstrations, regolith characterization, volatile detection, lunar delivery services, analogue testing, and early robotic excavation prototypes. Recurring missions and payload opportunities will be critical to validating these technologies in the lunar environment.

5–10 years: Building on near-term progress in precursor capabilities, development could shift toward more integrated system demonstrations. Likely areas of progress include water-ice mapping, oxygen extraction, autonomous excavation, regolith processing, surface mobility, construction-material testing, and early-stage resource logistics. These activities will begin integrating

multiple stages of the ISRU value chain while remaining primarily demonstration-based rather than operational.

10–15+ years: Operational ISRU remains a longer-term objective. This stage entails reliable end-to-end extraction, processing, storage, distribution, and operational use of locally produced resources to support sustained lunar and deep-space infrastructure. Achieving this level of maturity will depend not only on technological progress but also on reliable surface power, communications, mobility, storage infrastructure, governance frameworks, and sustained customer demand. Long-term exploration architectures, including Artemis and the ILRS, illustrate the types of

infrastructure and demand signals that could support this phase, but they should not be interpreted as evidence of operational ISRU capability.

2.4.7

Acceleration Measures

The acceleration measures in Table 16 directly address the barriers identified earlier and outline the technical, governance, commercial, and operational actions needed to advance ISRU maturity.

Table 16: Overview of Acceleration Measures for ISRU

Barrier	Acceleration Measure
Governance uncertainty	Develop clearer frameworks for authorization and supervision, safety measures, non-interference principles, data sharing, environmental and heritage-site protection, waste management, and dispute-resolution mechanisms.
Technology immaturity	Prioritize targeted R&D and mission-aligned demonstrations supported by shared test-beds, standardized regolith simulants, robotic test fields, cryogenic facilities, integrated system validation, recurring lunar delivery missions, shared payload opportunities, and coordinated demonstration campaigns.
Economic ambiguity	Establish public anchor customers, milestone-based procurement, resource-data markets, credible commercial service pathways, long-term demand signals from Artemis and ILRS, and use CLPS-style procurement mechanisms to support regular demonstration cadence.
System complexity	Develop shared and interoperable surface infrastructure, including power, communications, mobility, storage, and logistics systems, alongside integrated test campaigns that validate complete operating architectures.
Risk allocation and insurability	Create clearer liability arrangements, risk-sharing mechanisms, operational standards, resource-quality benchmarks, and transparent performance data to support insurance and project financing.
Geopolitical fragmentation	Promote common principles for transparency, interoperability, sustainability, data exchange, environmental protection, and safety measures across different lunar infrastructure pathways.

2.5

Space Communications & On-Orbit Data Infrastructure

Space Communications and On-Orbit Data Infrastructure form the digital backbone of the space economy, enabling space systems to connect, process, secure, and deliver data across increasingly complex orbital and terrestrial networks.

2.5.1

Definition

Space Communications and On-Orbit Data Infrastructure encompass the systems, functions, and enabling technologies that enable space assets to transmit, receive, route, process, store, secure, and deliver information across orbital and terrestrial networks. The cluster covers the communication and data layer that connects satellites, spacecraft, ground stations, gateways, user terminals, data centers, cloud platforms, and mission operators. It describes both the movement and processing of data across the mission architecture, whether onboard spacecraft, between satellites, at the network edge, through ground infrastructure, and within cloud-enabled systems.

The capabilities support a wide range of missions and services, including satellite broadband, narrowband connectivity, EO, mission operations, deep-space communications, cislunar activity, space station operations, encrypted communications, emergency response, and future in-space industrial activities. Across

these use cases, the core functions include command and control, telemetry, payload data downlink, user connectivity, intersatellite links, mesh networking, data relay, routing, synchronization, encryption, interference management, edge processing, onboard storage, and network orchestration.

The cluster is enabled by multiple technology families rather than a single communication pathway. These include radio frequency (RF) and optical links, fixed and steerable antennas, phased arrays, software-defined radios, modulation and coding technologies, onboard processors, application-specific integrated circuits (ASICs), ARM-based processors, field-programmable gate arrays (FPGAs), memory and storage systems, hypervisors, orchestrators, cybersecurity tools, and anti-jamming and interference-suppression technologies. The appropriate architecture depends on mission requirements, including bandwidth, latency, pointing accuracy, resilience, security, and cost. Collectively, these capabilities enable space systems to operate as connected, resilient, and increasingly autonomous networks rather than as isolated assets.

2.5.2

Maturity Level

The overall maturity of Space Communications & On-Orbit Data Infrastructure is medium-high, though it varies considerably across its sub-capabilities. Traditional satellite communications, broadcasting, established GEO and MEO services, narrowband LEO systems, and ground-segment services are commercially mature. Large-scale LEO broadband, cloud-integrated ground infrastructure, software-defined payloads, phased-array terminals, and selected RF and optical intersatellite links are operational and scaling. By contrast, globally interoperable Non-Terrestrial Networks (NTN), seamless multi-orbit and multi-operator orchestration, optical relay networks at scale, distributed orbital edge computing, space-based data centers, and quantum-ready secure networks remain at lower levels of maturity.

Among the five priority technologies assessed in this report, Space Communications and On-Orbit Data Infrastructure has the strongest overall readiness profile. The survey produced scores of 3.75/5 for technology readiness, 4.50/5 for market readiness, 3.25/5 for policy fit, 3.25/5 for time to maturity, and 4.75/5 for cross-cutting potential, resulting in an overall score of 3.90/5. These findings

reflect a technology cluster with substantial commercial deployment, strong market demand, and broad relevance across the space economy. However, its more advanced infrastructure layers will depend on improved interoperability, spectrum coordination, cyber resilience, orbital sustainability, and viable commercial models.

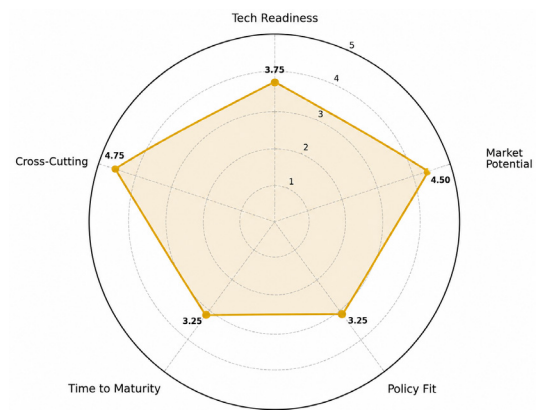


Figure 7: Maturity Level for Space Communications & On-Orbit Data Infrastructure, CSF Survey Results, 2025

Table 17 presents indicative maturity assessments for the principal technological capabilities in this cluster.



Table 17: Indicative Maturity Assessment per Technological Pillar of Space Communications & On-Orbit Data Infrastructure

Capability	Stage of Adoption	TRL	MRL	Mkt-RL	Commercial Solution	Illustrative Case
Established GEO/MEO broadband, broadcasting, and narrow-band satellite communications	Operational and commercial	9	9	9	Yes	SES, Intelsat, ViaSat, Eutelsat, Arabsat, Iridium, DirecTV, Globalstar, and other operators provide mature communications services across broadcasting, broadband, narrowband, mobility, government, and enterprise markets. These services are commercially established, although routine interoperability across operators remains limited.
Large-scale LEO broadband constellations	Operational and scaling	9	8–9	8–9	Yes, primarily within proprietary operator networks	OneWeb and Starlink ⁹⁰ are operational at scale. Their continued expansion is increasing broadband capacity, geographic reach, user-terminal availability, and intersatellite connectivity. However, interoperability and service orchestration across independently operated constellations remain limited.
RF intersatellite links and constellation networking	Operational in established networks and scaling in newer constellations	8–9	7–9	7–8	Yes, mainly within individual networks	RF crosslinks are operational in systems such as Iridium and other government and commercial networks. They enable routing and data relay within constellations, but standardized connectivity across independently operated networks remains limited.

Capability	Stage of Adoption	TRL	MRL	Mkt-RL	Commercial Solution	Illustrative Case
Optical inter-satellite links and data-relay network	Operational in selected systems and moving into wider deployment	7–9	6–8	5–7	Partial and expanding	Optical intersatellite links are increasingly deployed in newer constellations and relay architectures. ESA's European Data Relay System ⁹¹ demonstrates operational laser data relay, while Starlink ⁹² and the Space Development Agency ⁹³ are deploying optical links at constellation scale. The principal challenges are operational reliability, standardized interfaces, network integration, and interoperability across operators.
Optical space-to-ground communications	Demonstrated and entering limited operational adoption	6–8	5–7	4–6	Limited commercial availability	Optical space-to-ground communications can provide substantially higher data rates than conventional RF systems. However, operational availability remains constrained by cloud cover, atmospheric turbulence, pointing accuracy, and limited optical ground-station coverage. NASA ⁹⁴ states that optical communications can support data rates 10–100 times higher than comparable RF systems.
Software-defined payloads and digital beam-forming	Operational in advanced systems and scaling commercially	8–9	7–8	7–8	Yes	Software-defined satellites and digital payloads are increasingly used to reconfigure capacity, coverage, frequency allocation, and bandwidth after launch, improving operational flexibility and market responsiveness. More advanced cross-network and fully virtualized payload orchestration remains less mature.

Capability	Stage of Adoption	TRL	MRL	Mkt-RL	Commercial Solution	Illustrative Case
Standards-based 5G non-terrestrial networks	Standards defined; with early commercial deployment and integration	6–8	5–7	5–6	Emerging	3GPP ⁹⁵ Release 17 introduces specifications for satellite access within 5G systems. Initial services and trials demonstrate growing integration between terrestrial and satellite networks, but seamless global mobility, multi-operator interoperability, and higher-capacity direct-to-device services remain emerging.
Future 6G Terrestrial-satellite integration	Research, standards development, and early experimentation	3–5	2–4	2–4	No established commercial solution	6G concepts are expected to integrate terrestrial, aerial, and satellite infrastructure more deeply than current 5G NTN architectures. However, technical requirements, standards, spectrum arrangements, network architectures, and commercial models remain under development.
Direct-to-device satellite connectivity	Early commercial services, with broader cellular integration emerging	7–9	6–8	5–7	Partial and expanding	Direct-to-device services are moving from emergency messaging and limited text connectivity toward broader cellular integration. Apple's Emergency SOS via satellite ⁹⁶ demonstrates operational consumer service, while mobile operators and satellite providers are testing wider direct-to-device applications. Routine broadband service, global device compatibility, spectrum coordination, and seamless roaming remain less mature. ⁹⁷

Capability	Stage of Adoption	TRL	MRL	Mkt-RL	Commercial Solution	Illustrative Case
Onboard processing and data storage	Operational and scaling across commercial and institutional missions	8–9	7–8	6–8	Yes, with mission-specific limitations	Onboard processing supports data compression, filtering, AI inference, event detection, autonomous tasking, and reduced downlink demand. These capabilities are already operational, although performance remains constrained by radiation tolerance, power, thermal management, storage capacity, and the availability of flight-qualified processors and software.
Distributed orbital edge computing	Demonstration and early operational experimentation	5–7	4–6	3–5	Emerging	Distributed orbital edge computing would allow multiple spacecraft or hosted processing nodes to share, route, and process workloads in orbit. Early demonstrations are exploring onboard cloud services and edge AI, but routine distributed computing across orbital networks has not yet reached broad operational adoption.
Space-based data centers and large-scale orbital computing	Concept development and early demonstration	3–5	2–4	2–4	No established commercial solution	Proposed space-based data centers aim to provide large-scale processing, storage, or data-hosting capacity in orbit. Their viability remains uncertain because of launch and replacement costs, power availability, thermal rejection, radiation exposure, servicing requirements, downlink economics, and competition from terrestrial data centers.

Capability	Stage of Adoption	TRL	MRL	Mkt-RL	Commercial Solution	Illustrative Case
Ground-segment-as-a-service and cloud-integrated ground networks	Operational and commercial	8–9	7–9	8–9	Yes	Commercial ground-station networks and cloud-integrated ground-segment services are increasingly used for scalable data delivery, mission operations, and customer access. Further maturity is still required for secure cross-provider interoperability, automated scheduling across multiple networks, and integration of highly sensitive government workloads.
Cyber-resilient and protected satellite communications	Operational in government, defense, and selected commercial systems	8–9	7–9	7–8	Yes, although protection levels vary by system	Secure links, encryption, anti-jamming, cyber monitoring, authentication, and resilient routing are established in protected satellite systems. Wider adoption is constrained by cost, export controls, fragmented security requirements, legacy infrastructure, and evolving cyber threats.
Quantum-secure and quantum-ready space networks	Demonstration, government-led development, and R&D	4–6	3–5	2–4	Limited and experimental	Space-based quantum communications and quantum key distribution have been demonstrated in selected missions. ⁹⁸ However, scalable quantum-secure networks require improved hardware reliability, trusted-node architectures, ⁹⁹ standards, ground infrastructure, interoperability, ¹⁰⁰ and integration with conventional communications networks.

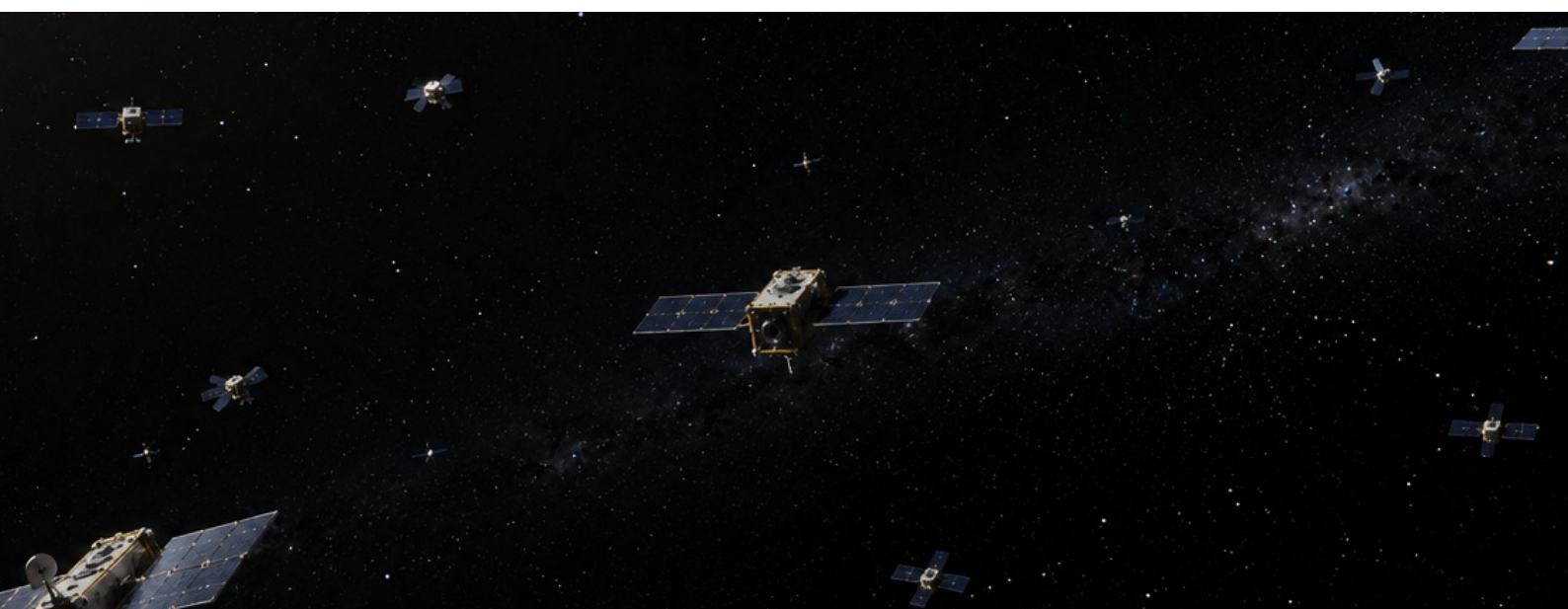
Capability	Stage of Adoption	TRL	MRL	Mkt-RL	Commercial Solution	Illustrative Case
Multi-band and multi-orbit RF antennas	Operational, with multi-band and multi-orbit systems scaling	8–9	7–8	7–8	Yes, although terminals are often optimized for specific bands, platforms, or networks	Multi-band RF antennas support S/X/Ka/Ku/UHF missions, improving flexibility, redundancy, and spectrum use. Airbus has deployed multi-band satellite payload configurations, ¹⁰¹ while Kymeta is developing Ku/Ka multi-band flat-panel terminals. ¹⁰² Low-cost terminals capable of switching seamlessly across bands and operators remain less mature.
User equipment: phased arrays	Operational and rapidly scaling	8–9	8–9	8–9	Yes	Electronically steered flat-panel/phased-array terminals enable low-profile, mobile, and LEO-tracking connectivity. Starlink user terminals use electronic phased-array antennas; ¹⁰³ Kymeta ¹⁰⁴ and BAE Systems offer flat-panel / Ku-Ka electronically steered terminals. ¹⁰⁵ Single-network terminals are commercially mature, while affordable multi-band and multi-orbit terminals remain at an earlier stage.
Hybrid terrestrial satellite network management and Software-defined networking (SD-WAN)	Commercial for managed enterprise networks; expanding toward multi-orbit orchestration	8–9	7–8	7–8	Yes	SD-WAN enables satellite links to be managed as part of hybrid terrestrial, cloud and enterprise networks, improving resilience and routing flexibility. Intelsat Flex-Enterprise supports SD-WAN and hybrid connectivity use cases. ¹⁰⁶ Current solutions are generally managed within specific provider ecosystems, while automated orchestration across independent terrestrial, GEO, MEO, and LEO networks remains emerging.

Capability	Stage of Adoption	TRL	MRL	Mkt-RL	Commercial Solution	Illustrative Case
Multi-orbit and multi-operator network orchestration	Early deployment within proprietary ecosystems; limited across independent operators	6–8	5–7	4–6	Partial	Multi-orbit orchestration enables traffic and capacity to be managed across GEO, MEO, LEO, terrestrial, and cloud-enabled networks. ¹⁰⁷ Operators are beginning to offer integrated services across their own assets and partner networks, but routine interoperability, common interfaces, secure service exchange, and terminal compatibility across independent operators remain limited. ¹⁰⁸

The most mature capabilities in this cluster include broadcasting, broadband, and narrowband satcom; established GEO and MEO services; selected LEO communications systems; ground-segment services; protected communications; and mission-proven deep-space communication systems. Large-scale LEO broadband, phased-array terminals, software-defined payloads, cloud-integrated ground infrastructure, optical intersatellite links, and standards-based 5G NTN are operational or moving through rapid commercial expansion.

The less mature capabilities require integration across networks, operators,

and infrastructure layers. These include seamless direct-to-device connectivity, hybrid terrestrial-satellite 5G and future 6G networks, large-scale optical relay, automated multi-orbit orchestration, and distributed orbital edge processing. The earliest-stage capabilities include space-based data centers, quantum-ready networks, and highly autonomous orbital data infrastructure. Their development depends not only on technical progress but also on interoperability standards, secure architectures, viable operating models, and clear commercial demand.



2.5.3

Key Technical and Operational Barriers

The maturity of Space Communications and On-Orbit Data Infrastructure is constrained by a combination of technical, regulatory, operational, and commercial challenges. Although many communication technologies are already deployed commercially, future architectures increasingly depend on interoperability, resilient infrastructure, secure data exchange, and coordinated governance across multiple operators and jurisdictions. The principal barriers are therefore systemic and mutually reinforcing.

1. Spectrum access and regulatory coordination

Spectrum underpins every satellite communications service, from broadband and narrowband connectivity to the transmission of EO data, intersatellite links, direct-to-device services, and deep-space communications. Demand for spectrum is rising rapidly, while allocation and coordination processes remain lengthy and internationally complex. The workshop identified spectrum availability, regulatory coordination, and a lack of harmonized interoperability standards as key constraints on deployment. The survey identified RF interference and spectrum coordination as significant risks to the continued expansion of this technology cluster. These constraints can delay network deployment, limit available capacity, and complicate the introduction of services operating across multiple countries and orbital regimes.

2. Interoperability and fragmentation

Many satellite systems continue to rely on vertically integrated architectures and proprietary interfaces. Without common technical standards for frequency use, modulation, routing, security, optical terminals, and user equipment, the risk of creating parallel infrastructure layers that cannot communicate increases.¹⁰⁹ This issue can reinforce vendor lock-in, reduce

equipment compatibility, and weaken resilience across multi-operator and multi-orbit architectures. Earlier mobile markets illustrate the consequences of incompatible standards. GSM enabled broad international roaming across participating networks, but devices generally could not operate seamlessly across GSM, CDMA, and other incompatible systems, requiring separate equipment ecosystems.¹¹⁰ Similar fragmentation in satellite communications could limit terminal compatibility, constrain service continuity across operators and orbital regimes, and prevent multi-orbit networks from functioning as integrated communications infrastructure.

3. Cybersecurity and contested-space resilience

The survey focused on security threats, including jamming, spoofing, and cyberattacks, particularly in contested environments. As space infrastructure becomes more tightly integrated into government, emergency response, financial systems, critical infrastructure, cloud services, and autonomous space operations, maintaining cyber resilience is essential for commercial continuity, infrastructure security, and strategic resilience. The growing integration of satellite, terrestrial, cloud, and user networks also expands the attack surface and creates dependencies across multiple infrastructure layers.

4. Orbital congestion and space environment risk

Growing orbital congestion threatens the long-term resilience of space communications infrastructure, particularly in LEO, where large constellations increasingly provide low-latency connectivity and data relay. Workshop discussions identified collision risk, debris generation, inadequate end-of-life disposal, anti-satellite testing, and the lack of binding international debris-management requirements as key concerns. Together, these factors increase operational risk and raise the cost and complexity of maintaining resilient communications networks. They can also disrupt service continuity, shorten asset life, increase replacement requirements, and constrain access to heavily used orbital regions.

5. Optical-link reliability and ground constraints

Optical communications offer higher data rates and reduce spectrum pressure, but they require precise pointing, acquisition, and tracking. Space-to-ground links can be affected by clouds, weather, and atmospheric turbulence. As a result, optical infrastructure requires geographically distributed optical ground stations, hybrid RF-optical architectures, and intelligent link switching. These constraints increase infrastructure costs and reinforce the need for hybrid networks that can dynamically select between RF and optical pathways based on link availability and mission requirements.

6. Market concentration and infrastructure control

Rapid investment in communications constellations is intensifying competition while also increasing the risk that infrastructure control becomes concentrated among a small number of vertically integrated providers. Workshop discussions highlighted concerns that high capital requirements, spectrum access, orbital resources, terminal ecosystems, and integrated data platforms may confer structural advantages on a limited number of operators. Such concentration could reduce competition, increase vendor dependence, limit customer choice, and restrict interoperability across the broader ecosystem. It may also give individual providers substantial control over communications capacity, user access, data routing, and associated digital services.

7. Economic uncertainty in space-based data centers and orbital computing

While onboard processing and edge computing already offer clear operational benefits, the commercial viability of large-scale orbital data centers remains uncertain. Key concerns include power, thermal control, launch and replacement costs, radiation tolerance, data sovereignty, latency economics, and customers' willingness to pay. The survey explicitly flagged space data centers as potentially overhyped because of ambiguous economics and the challenges posed by power and thermal constraints. Their value proposition will hinge on whether orbital computing can deliver sufficient advantages in latency, data processing,

resilience, sovereignty, or energy use to offset substantially higher deployment and operating costs. Until these technical and commercial uncertainties are resolved, large-scale orbital computing should be regarded as a longer-term opportunity rather than an established market.

2.5.4

Market Potential and Strategic Relevance

Space Communications and On-Orbit Data Infrastructure represent one of the strongest near-term commercial opportunities within the priority technology clusters, though the opportunity is uneven across its capabilities. Unlike several emerging space technologies that depend on future market creation, demand for connectivity, data transmission, secure communications, and digital infrastructure is already well established across commercial and government sectors. Near-term growth is likely to remain concentrated in LEO broadband, high-throughput GEO and MEO services, cloud-integrated ground infrastructure, software-defined payloads, phased-array terminals, and protected communications. Medium-term opportunities emerge around direct-to-device connectivity, hybrid terrestrial-satellite networks, optical communications, secure data-relay services, and onboard edge processing. Longer-term opportunities in distributed orbital computing, quantum-ready networks, and space-based data centers will depend on technical feasibility, viable economics, and credible customer demand.

Table 18 summarizes indicative public market estimates for selected segments of the communications and orbital data infrastructure ecosystem. The figures should be viewed as directional indicators rather than directly comparable forecasts, given differences in market definitions and methodologies. They represent selected segments of the cluster and should not be combined into a single estimate of its total market value.

Table 18: Overview of Market Report Insights into Space Communications & On-Orbit Data Infrastructure

Source	Market Scope	Market Size and Growth	Strategic Interpretation
Grand View Research ¹¹¹	Global satcom market	Valued at \$98.3B (2025); projected to grow from \$107.4B (2026) to \$223.1B (2033); CAGR 11.0%	Indicates a large, established commercial market spanning services, equipment, broadband, mobility, government, and enterprise connectivity. The scale of the estimate confirms that the strongest near-term opportunity lies in communications services and supporting infrastructure.
MarketsandMarkets ¹¹²	Communication small satellites	Projected to grow from \$5.95B (2025) to \$18.34B (2030); CAGR 25.2%	Points to rapid growth in communication-focused small-satellite systems, including constellations supporting broadband, narrowband, relay, and low-latency connectivity
MarketsandMarkets ¹¹³	Optical / laser satcom	Projected to grow from \$0.62B (2025) to \$1.56B (2030); CAGR 20.4%	Indicates strong expected growth in optical terminals, high-capacity links, and laser intersatellite networking, although from a relatively smaller base and before broad commercial adoption.
Mordor Intelligence ¹¹⁴	Optical satcom	Projected to grow from \$1.56B (2025) to \$4.45B (2030); CAGR 23.36%	Reinforces expectations of rapid optical-communications growth, while the difference from other estimates illustrates how market boundaries vary across equipment, infrastructure, and service definitions.
Fortune Business Insights ¹¹⁵	Space-based data center market	Valued at \$1.28B (2025); projected to grow from \$1.44B (2026) to \$3.81B (2034); CAGR 12.96%	Indicates commercial interest and anticipated investment rather than an established market. The segment remains speculative because its technical feasibility, operating economics, customer demand, and comparative advantage over terrestrial infrastructure have not yet been demonstrated at scale.

Although North American and European organizations continue to shape much of the commercial market, the development of space communications and orbital data infrastructure is increasingly global. Alongside established commercial constellations and institutional programs, governments and industry across Asia, the Gulf, Russia, Africa, and other regions are investing in sovereign communications capabilities, regional service provision, and next-generation orbital infrastructure. Table 19 provides an indicative overview of this expanding global landscape.

Table 19: Representative Global Developments in Space Communications and Data Infrastructure

Region / State	Capability Focus	Adoption Stage	Maturity	Illustrative Example
China	Large-scale LEO broadband, narrowband connectivity, satellite IoT, and optical and quantum communications demonstrations	Scaling rapidly and unevenly across constellations	Medium-high for deployment; medium for broad commercial service availability	Geespace¹¹⁶ has completed Phase I deployment of GEE satcom, a LEO IoT constellation with 64 satellites in orbit by September 2025. GalaxySpace¹¹⁷ develops low-cost mass-production LEO broadband satellites and has initiated a small LEO broadband constellation. SpaceSail/Qianfan¹¹⁸ is being positioned as a Chinese large-scale LEO broadband system.
India	Regional GEO satellites providing satellite broadband services, GSaaS, investments in optical communications, and an expanding private EO/data infrastructure	Active commercially; regulatory framework expanding private participation	High for established satellite services; medium for advanced indigenous data infrastructure	India has operated GEO communications satellites for more than three decades. Its regulatory regime now includes foreign providers (licensed Starlink Satcom Pvt. Ltd., Jio Satcom Ltd., and OneWeb India Communications Pvt. Ltd.¹¹⁹ for satellite internet services). Dhruva Space¹²⁰ offers satellites, Earth stations, and launch services, while Astrogate Labs¹²¹ develops laser communication terminals for space, air, and terrestrial networks.
Japan	Mature GEO satcom, optical data relay, cloud ground segment, and optical and quantum communications development	Operational in GEO; emerging in optical relay and GSaaS	High for GEO; medium for optical/data relay	SKY Perfect JSAT¹²² is a major Asian satellite operator providing broadcasting, broadband, and narrowband services. Space Compass¹²³ is developing optical data relay services. WarpSpace¹²⁴ is developing optical intersatellite data relay. These systems remain under development rather than operational at commercial scale.

Region / State	Capability Signal	Stage of Adoption	Indicative maturity	Cases
Russia	Mature GEO communications and broadcasting services, civil LEO messaging and data relay, and sovereign connectivity systems	Operational in GEO; limited global commercial transparency	Medium-low for global LEO broadband; mature heritage for store-and-forward systems	Bureau 1440¹²⁵ is developing a software-hardware complex for data exchange between orbital satellite constellations and ground public networks. Gonets¹²⁶ provides near-global satcom coverage and remains Russia's main civil LEO communication system.
Africa	Regional satellite capacity, connectivity service integration, LEO distribution, broadband for remote and underserved areas	Commercial deployment and service integration; limited indigenous orbital infrastructure	Medium for service delivery; low-medium for indigenous orbital systems	NIGCOMSAT¹²⁷ owns and operates Nigeria's communications satellite system. Nilesat¹²⁸ provides DTH broadcasting, satellite broadband, and communications services across Egypt and the MENA region. Q-KON/Twoobii¹²⁹ distributes Eutelsat OneWeb LEO connectivity in Africa. Liquid Intelligent Technologies,¹³⁰ Vodacom¹³¹ and Airtel Africa¹³² are integrating LEO satellite connectivity and direct-to-cell services into African telecom markets.
Gulf / MENA	GEO satcom, mobility, broadband, sovereign digital infrastructure, in-flight connectivity	Operational and commercially mature in GEO/service layers	High for regional satcom; emerging for broader digital space infrastructure	Arabsat¹³³ operates a regional satellite fleet and provides voice, video, and data coverage across more than 100 countries. Space42¹³⁴ (formerly Yahsat/Thuraya) provides broadband, narrowband, mobile, and government satcom across more than 150 countries. Es'hailSat¹³⁵ serves the MENA region with broadband, mobility, and telecom services. Neo Space Group¹³⁶ provides satellite communications and geospatial services in Saudi Arabia.

The strategic value of Space Communications and On-Orbit Data Infrastructure extends beyond commercial connectivity. As digital infrastructure becomes more deeply integrated into economic activity, government operations, critical infrastructure, and autonomous systems, resilient satellite communications are evolving from a standalone service to a foundational layer of the broader digital economy. Four broad service families illustrate this strategic role.

1. Extending connectivity beyond terrestrial networks

Satellite communications provide coverage for rural and remote regions, maritime and aviation operations, offshore energy infrastructure, mining sites, border areas, and disaster-affected zones where terrestrial networks are unavailable, damaged, or too costly to deploy. Their value lies not only in expanding coverage but also in maintaining access to communications when terrestrial infrastructure is impractical or disrupted.

2. Enabling secure and mission-critical communications

Secure communications technologies and resilient satellite connectivity support government, diplomacy, homeland security, emergency response, and critical infrastructure operations. In these contexts, the value extends beyond bandwidth to include continuity of service, redundancy, secure access, and resistance to disruption. These capabilities are especially important where service loss could affect public safety, essential operations, or infrastructure continuity.

3. Supporting machine-to-machine connectivity and autonomous systems

Satellite and orbital networks enable connectivity among satellites, sensors, vehicles, industrial assets, and remote devices. This includes IoT, intersatellite links, Earth-observation data relay, autonomous systems, ISAM operations, and distributed space architectures that require reliable data exchange among machines, platforms, and ground systems. As these systems become more autonomous, communications and data infrastructure must support lower-

latency exchange, onboard decision-making, and coordinated operations across multiple assets.

4. Integrating satellite and terrestrial digital infrastructure

Satellite systems are increasingly integrated into terrestrial telecom networks through 5GNTN, future 6G architectures, direct-to-device services, hybrid networks, and SD-WAN-enabled architectures. This integration enables satellites to serve as a coverage extension, a resilience layer, or an emergency backup for terrestrial networks, supporting first responders, mobility users, enterprises, and future cloud and data-distribution services. Its long-term value will depend on whether users can move securely and seamlessly across terrestrial, satellite, cloud, and multi-orbit networks.

Collectively, these service families position Space Communications and On-Orbit Data Infrastructure as a foundational enabler of sovereign digital infrastructure, supporting economic competitiveness, national resilience, public services, and future space operations.

2.5.5

Cross-Cutting Applications

Space Communications and On-Orbit Data Infrastructure both draw on and contribute to capabilities developed across multiple terrestrial industries. Advances in telecommunications, cloud computing, cybersecurity, artificial intelligence, photonics, and digital infrastructure are increasingly adapted for space applications, while innovations developed for space systems can generate broader commercial, industrial, and societal value beyond the space sector. Table 20 illustrates how selected technology domains support space-sector use cases and create downstream value beyond the space economy.

Table 20: Cross-Cutting Applications of Space Communications & On-Orbit Data Infrastructure

Cross-Cutting Area	Terrestrial Capability (Spin-In)	Space Application	Terrestrial Benefits (Spin-Off)
Telecommunications and 5G/6G integration	Terrestrial cellular standards; network slicing; software-defined networking; cloud-native telecom; 3GPP NTN; edge architectures	Satellite broadband networks, dynamic service prioritization, direct-to-device, 5G/6G NTN, and space-terrestrial network integration	Expanded rural connectivity, resilient telecom backhaul, disaster-recovery networks, and hybrid terrestrial-satellite services. Space-based NTN development can also strengthen terrestrial standards for coverage continuity, roaming, and network resilience.
Cloud computing and edge AI	Cloud platforms; distributed computing; AI inference, data compression; virtualization, orchestration; edge analytics	Onboard processing architectures; cloud-integrated ground segments; event-based EO tasking; AI-enabled data prioritization; reduced downlink load	Lower-latency analytics for actionable intelligence (e.g., agriculture, energy, smart cities, disaster response and logistics). More efficient processing of data from remote and bandwidth-constrained environments.
Optical communications and photonics	Fiber optics; laser terminals; adaptive optics; photonic chips; precision pointing technologies	Laser ISLs; optical space-to-ground links; high-capacity relay; quantum-ready connectivity	Advances in compact photonics, precision pointing, secure optical links, and high-capacity data transfer can support terrestrial telecom networks, data-center interconnects, and remote optical communications.
Cybersecurity and critical infrastructure protection	Zero-trust architectures; encryption; intrusion detection; anti-jamming, authentication; secure routing; cyber-resilient control systems	Secure satcom; protected data links; resilient command-and-control; interference detection; cyber-resilient space networks	Stronger cyber protection for energy grids, telecom networks, ports, aviation, finance, and emergency services. Space system requirements can also advance resilient architectures for distributed and remotely operated infrastructure.
Secure and Resilient Infrastructures	Protected communications; ISR data fusion; resilient mesh networks; secure networking; operations in disrupted or contested environments	Software-defined architecture (SDA)-style transport layers; secure relay; missile-warning; ISR dissemination beyond-line-of-sight tactical links	Improved emergency communications, border security, maritime domain awareness, and critical infrastructure monitoring.

Cross-Cutting Area	Terrestrial Capability (Spin-In)	Space Application	Terrestrial Benefits (Spin-Off)
EO and climate services	Big data analytics; geospatial platforms; AI image processing; real-time monitoring systems	Real-time EO downlink; disaster-response relay; climate monitoring; precision agriculture; environmental compliance	Faster wildfire detection, flood monitoring, food security, urban planning, and environmental enforcement. Improved communications and onboard processing can shorten the time between observation and action.
Autonomous systems and robotics	Autonomous vehicles; drones; industrial IoT; maritime autonomy; remote operations	Coordination of satellite swarms; autonomous ISAM; lunar robotics; cislunar logistics; distributed sensing.	Resilient communications for autonomous transport, mining, offshore energy, and remote industrial operations. Space-qualified autonomy and networking can also inform systems designed to operate with limited connectivity and human intervention.
Financial services and insurance	Risk analytics; continuity planning; secure data transport; asset monitoring; parametric insurance	Satellite asset assurance; space traffic data relay; critical mission continuity; insurable connectivity services	Better risk pricing for infrastructure, climate exposure, logistics, agriculture, and disaster recovery. More reliable satellite data and service-performance records can improve risk assessment, enable parametric products, and support insurance coverage for connectivity-dependent operations.
Smart cities and infrastructure	IoT; digital twins; urban analytics; utility monitoring; connected infrastructure	Space-enabled connectivity; EO data flows for smart-city management; infrastructure monitoring	More resilient cities; remote infrastructure maintenance; integrated digital public services. Space-derived monitoring and communications can improve oversight of transport, utilities, public safety, and geographically dispersed assets.

The breadth of applications in Table 20 underscores the role of Space Communications and On-Orbit Data Infrastructure as a foundational enabler of the broader space economy. Its influence extends well beyond connectivity, supporting digital infrastructure, critical services, industrial operations, and emerging autonomous systems. The cluster also benefits from continuous two-way technology transfer: terrestrial advances accelerate space-network development, while space requirements drive improvements in resilience, autonomy, secure communications, and remote operations. This broad applicability is reflected in the survey, which ranked the cluster highest for cross-cutting potential among the five priority technology areas.

2.5.6

Time to Maturity

The following timeframes are indicative of the relative maturity of the technological capabilities assessed in this cluster.

They should not be interpreted as forecasts, but as plausible development pathways shaped by the pace of investment, deployment, standards development, regulatory coordination, and commercial demand. Progress is expected to remain uneven, with established communications services scaling well before advanced

orbital data infrastructure reaches routine operation.

3–5 years: Commercially mature technologies are expected to scale through broader deployment. These include RF communications for LEO broadband, high-throughput GEO and MEO services, more affordable and simplified phased-array terminals, cloud-integrated ground segments, software-defined payloads, secure and resilient mesh networks, and expanded onboard processing and limited edge AI. Demand for these capabilities is already established across commercial and institutional markets and is expected to continue growing. Progress during this period will focus primarily on greater scale, lower cost, wider geographic availability, and improved integration rather than on the initial validation of underlying technologies.

5–8 years: The focus is likely to shift from expanding individual services to integrated communications across terrestrial, satellite, and orbital networks. Direct-to-device connectivity and standards-based 5G NTN services could extend beyond limited messaging, while optical relay, onboard edge AI, and secure data-relay services could enable faster, more autonomous data exchange. Progress toward resilient multi-orbit networks and advanced user equipment will depend on stronger interoperability, coordinated spectrum access, and business models that support service delivery across multiple operators and networks.

8–10+ years: The next stage of development would move beyond connected networks toward orbital infrastructure capable of processing, routing, and managing data with greater autonomy. Distributed edge computing could reduce reliance on continuous downlink, while advanced multi-network terminals and autonomous orchestration could enable users and spacecraft to move more seamlessly across different communications systems. Quantum-ready networks may also advance through larger demonstrations and early operational applications. Space-based data centers are likely to remain the least certain capability in this period because their viability depends on major advances in power, thermal management, servicing, and

cost competitiveness relative to terrestrial infrastructure.

2.5.7

Acceleration Measures

Accelerating the development of this technology cluster will require coordinated action across regulation, technology, infrastructure, and market development. The principal measures include:

1. Streamlining spectrum and licensing pathways

Clearer, faster, and more predictable spectrum authorization is essential to reduce time-to-market and improve investor confidence. The workshop discussions identified lengthy spectrum allocation and limited spectrum availability as critical barriers. Greater coordination across jurisdictions will also be required for direct-to-device services, multi-orbit networks, and systems intended to operate across multiple national markets.

2. Developing interoperability standards

Common standards for user equipment, routing protocols, cybersecurity, service-level agreements, data formats, ground interfaces, and NTN integration are essential to prevent a fragmented communications infrastructure and enable interoperability across operators and orbital regimes. Priority should be given to multi-band terminals, optical communication interfaces, secure service exchange, roaming, and network orchestration across terrestrial, GEO, MEO, and LEO systems.

3. Expanding ground and relay infrastructure

Diversified RF and optical ground stations, regional gateways, cloud-integrated mission operations, and hybrid RF-optical networks are needed to improve coverage, availability, resilience, security, and data control. Shared or commercially accessible infrastructure could also lower entry barriers for emerging

operators and services.

4. Demonstrating integrated network architectures

More system-level demonstrations are needed to validate direct-to-device services, optical relay, multi-orbit routing, autonomous network management, onboard edge processing, and secure data exchange under realistic operating conditions. Demonstrations should test complete service architectures rather than isolated components and should generate operational evidence that supports customer adoption and regulatory approval.

5. Strengthening cybersecurity and resilience requirements

Embedding secure-by-design architectures, encryption, anti-jamming and anti-spoofing capabilities, incident-response planning, and cyber certification into mission authorization and procurement processes would strengthen the resilience of future communications infrastructure. Requirements should address the full architecture, including spacecraft, terminals, gateways, terrestrial networks, cloud systems, and third-party service providers.

6. Integrating orbital sustainability into network design

Large communication constellations require credible disposal plans, collision-avoidance procedures, traffic coordination, debris mitigation, and responsible end-of-life operations. These measures should be incorporated into constellation design, licensing, procurement, and operational planning rather than addressed only after deployment.

7. Creating credible demand for emerging services

Governments, institutional users, infrastructure operators, and large commercial customers can accelerate maturity through mission-linked procurement, early service contracts, co-funded demonstrations, and commitments tied to specific connectivity, resilience, or data-processing needs. Such demand signals are particularly important for optical

relay, secure multi-orbit services, advanced onboard processing, and regional ground infrastructure.

8. Clarifying the business case for orbital data infrastructure

Onboard edge processing has a strong operational rationale. In contrast, space-based data centers require cautious advancement, guided by validated use cases, customer commitments, power and thermal feasibility, and realistic cost models. Development should focus on applications where orbital processing offers a demonstrable advantage over terrestrial infrastructure, such as reducing downlink requirements, accelerating time-sensitive analysis, or processing data generated and consumed in space.

Overall, Space Communications and On-Orbit Data Infrastructure are the most commercially mature of the five priority technology clusters and a foundational enabler of the wider space economy. Its near-term value lies in expanding resilient broadband, narrowband, and secure connectivity, supported by cloud-integrated ground systems and increasingly efficient data delivery. Over the longer term, advances in autonomous communications architectures, distributed orbital computing, and next-generation data services have the potential to transform how space infrastructure supports economic activity, strategic resilience, and future space operations. Realizing that potential will depend on continued progress in spectrum governance, interoperability, cybersecurity, orbital sustainability, and commercially viable infrastructure models.

03

Decision-Making Dynamics Across Key Stakeholders

The trajectory of emerging space technologies is determined less by technical readiness and more by how public, financial, and industrial priorities converge or conflict.

Aligning public value, investor returns, and industrial competitiveness is critical to sustaining funding flows and enabling implementation at scale. Because these actors assess opportunities through different lenses, their alignment directly determines which technologies advance, stall, or remain confined to demonstrations. These dynamics are therefore foundational to market formation.

The implementation of emerging space technologies depends not only on technical readiness but also on access to capital and the confidence of those who allocate it. Each stakeholder group applies distinct criteria to decide whether to invest, adopt, partner, or scale a solution. This section provides a cross-cutting view of how different actors prioritize investment, adoption, partnership, and scaling decisions, and how their differing incentives shape the trajectory of emerging space technologies.

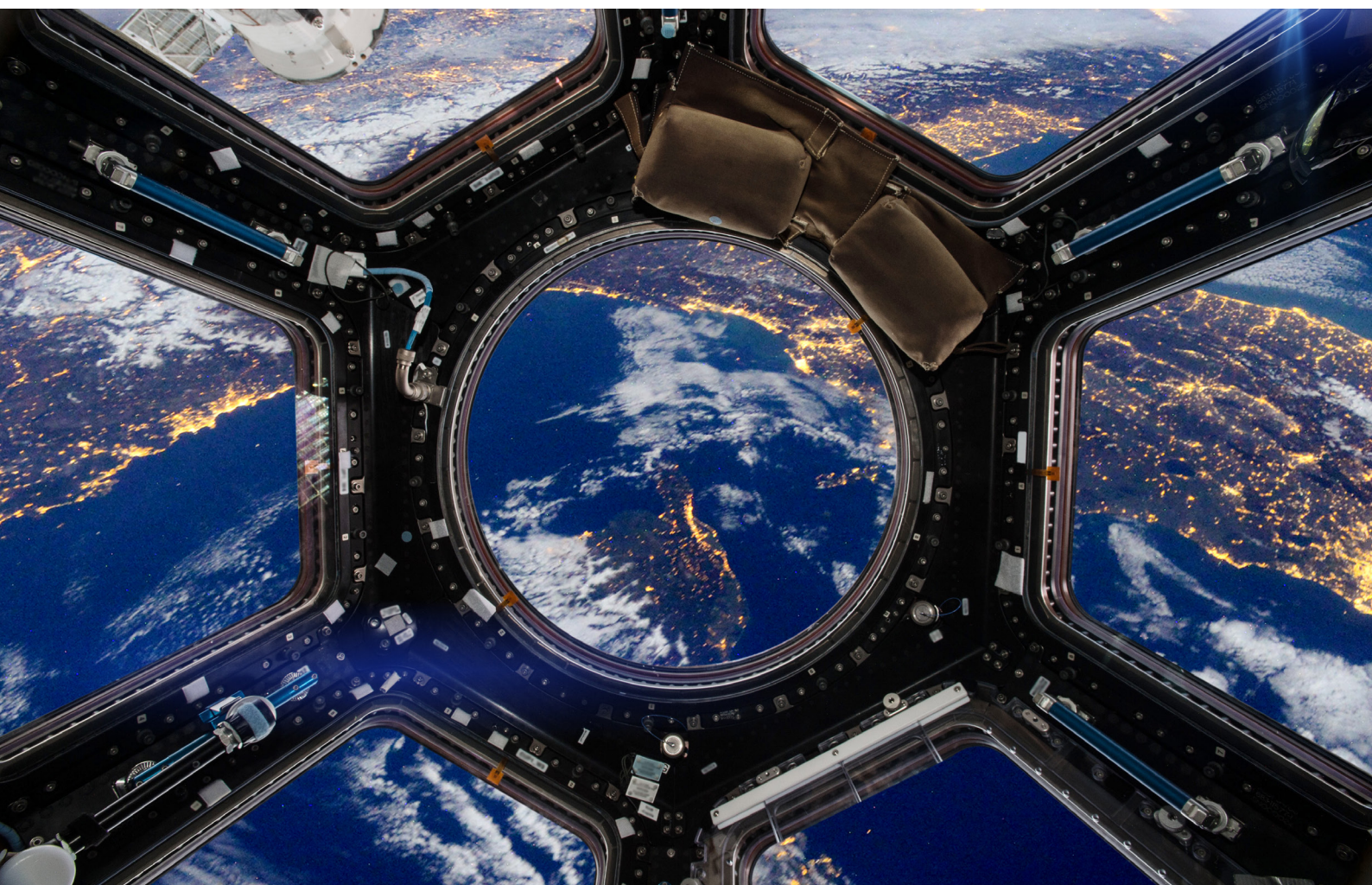
Public actors, including governments, ministries, and civilian and defense space agencies, often serve as anchor funders, customers, regulators, and capability builders. Their decisions are shaped by resilience, sovereignty, national capability development, long-term public value, and the responsible use of public resources. Financial actors provide capital through venture capital, private equity, corporate investment, and other financing mechanisms, assessing

opportunities based on risk-adjusted returns, scalability, commercial traction, and credible exit pathways. Industrial actors evaluate technologies based on operational value, integration requirements, and the ability to strengthen competitive advantage, secure supply chains, improve performance, or reduce costs. Because these groups operate under different mandates, constraints, and time horizons, their priorities are not interchangeable and can create friction across investment, procurement, adoption, and scaling decisions. These differences influence whether technologies attract sustained support and move beyond demonstrations. Table 21 summarizes the main priorities and decision-making considerations for each stakeholder group.

Table 21: Decision-Making Priorities Across Key Stakeholder Groups

Stakeholder Group	Primary Priorities	Decision-Making Considerations
Public Actors	Self-sufficiency, national capability development, and long-term public value.	Value for public expenditure, policy alignment, exposure to strategic dependencies, national capability gaps, societal impact, and delivery reliability
Financial Actors	Risk-adjusted returns, scalability, commercial traction, and credible exit pathways.	Revenue growth, burn rate, customer acquisition, margins and capital efficiency, and timing and probability of returns.
Industrial Actors	Competitive advantage, supply chain security, performance improvements, and cost efficiencies.	Unit economics, integration complexity, supplier concentration, operational reliability, and implications for market positioning.

The challenge lies in aligning these distinct priorities around a credible pathway to deployment. Without that alignment, promising technologies may fail to secure sustained funding, committed customers, or industrial adoption. Technical readiness is necessary but insufficient, as market formation ultimately depends on whether the requirements of each stakeholder group can be reconciled.



3.1 | Public Sector & Policymakers

Public sector decisions shape the direction and pace of emerging space technologies by balancing sovereignty, security, and long-term public value amid uncertainty and risk.

The public sector actively shapes the market through a dual role. First, it allocates public resources through funding, procurement, public-private partnerships, and program selection, choosing the technologies that best serve public-interest objectives.¹³⁷ Second, it regulates by setting the legal, technical, and operational conditions for the development, deployment, and commercialization of space technologies.

The first set of decision criteria concerns selection and expenditure. Public entities evaluate competing options against interdependent factors, including political stability, national security, service continuity, technological resilience, scientific and technological advancement, industrial development, job creation, and economic growth, with the objective of maximizing long-term national economic impact. This results in a best-value-for-money approach rather than selecting the lowest cost, with decisions based on the strongest combination of strategic relevance, performance, affordability, risk allocation, and long-term public benefit. This logic is reflected in space procurement practices that evaluate technical merit, management approach, affordability, and broader public-private value alongside price. These decisions are inherently trade-offs, where strategic importance, risk tolerance, and long-term value often outweigh short-term cost efficiency.

The second set of criteria concerns regulatory and standard-setting functions. Public authorities establish conditions for a safe, fair, and investable market by defining licensing regimes, safety and security requirements, responsibility and liability frameworks, insurance structures, and broader governance measures that protect users and the public interest. These frameworks not only constrain the market; they also enable it by reducing uncertainty, expanding participation, and establishing the conditions for scalable and investable innovation.

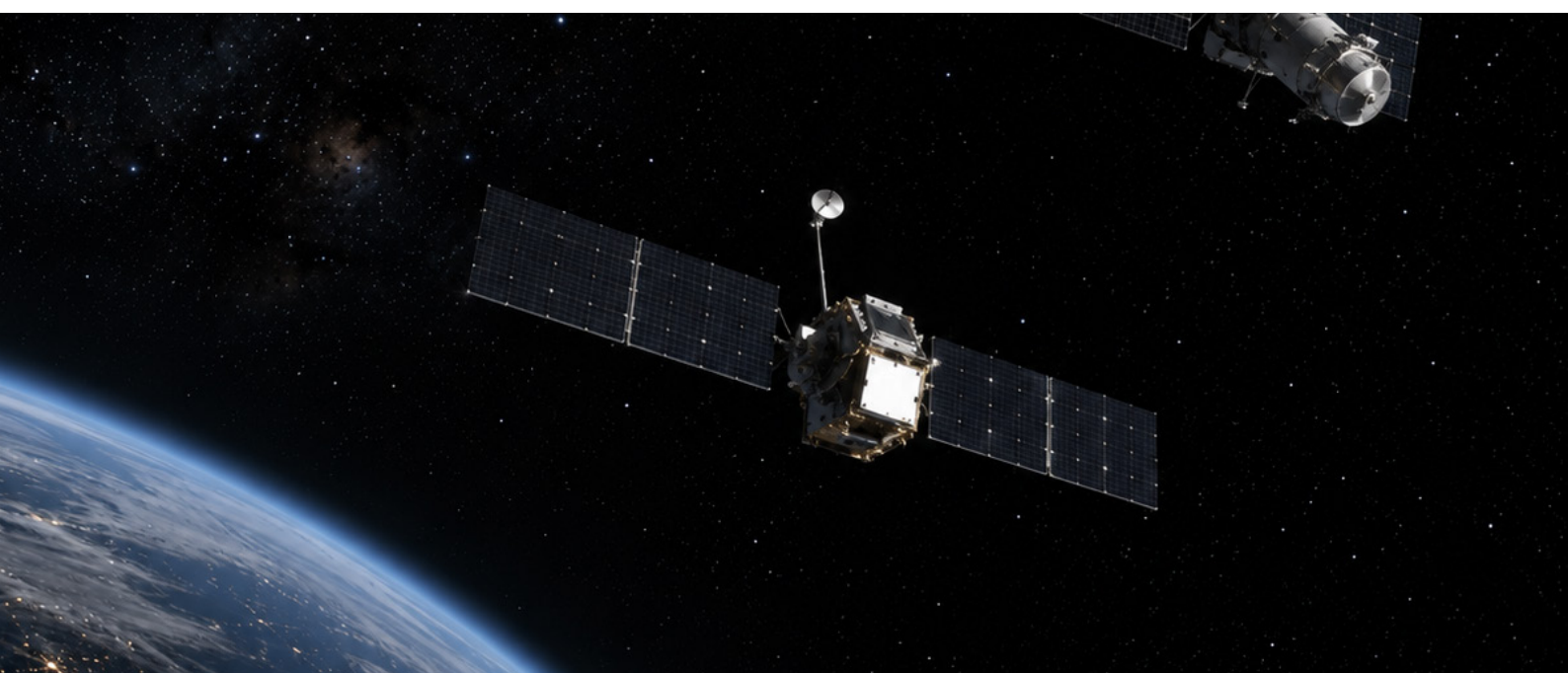
Table 22 summarizes the key decision drivers for public entities, supported by illustrative real-world cases.

Table 22: Public Sector Decision Criteria for Adopting Emerging Space Technologies

Public Sector Role / Decision Drivers	Key Considerations	Decision Logic	Illustrative Cases
Strategic Capability	Whether the technology reduces external dependency, strengthens secure national or regional infrastructure, and supports long-term critical services	Prioritize when the capability is strategically indispensable, even if the commercial case is still maturing	EU IRIS ² / SpaceRISE: ¹³⁸ Development of an EU-controlled multi-orbit satellite network to provide secure and reliable governmental connectivity, protect Europe's digital independence and reinforce strategic autonomy
Robustness and Continuity of Public Service	Contribution to secure communications, crisis response, civil protection, redundancy, and technological resilience against hybrid or cyber threats	Approve or accelerate when technology materially improves the continuity of essential governmental or societal services	US GPS: Early adoption and long-term commitment. EU Galileo Program: ¹³⁹ EU-controlled global navigation satellite services supporting positioning, navigation, and timing
Best Value for Money in Competitive Selection	Cost, technical merit, management quality, risk-sharing, schedule realism, and overall value to the government	Select when the proposal delivers overall value within budget, and reject or defer when technical merit does not justify the cost	NASA Human Landing System Option A: ¹⁴⁰ NASA concluded that Dynetics did not provide sufficient value at its evaluated price, given budget constraints
Innovation Acceleration and Phased Technology Maturation	Ability to structure procurement to absorb early failure risk while still advancing strategic capability and learning	Pilot first when the technology is promising and still immature; use phased, milestone-based, or service-based acquisition before full-scale commitment	NASA CLPS: ¹⁴¹ Use of firm-fixed-price task orders with commercial vendors, initially flying low-cost, non-critical payloads before progressing to more complex missions
Industrial Competitiveness, Jobs, and Ecosystem Growth	Contribution to domestic industry, Small and Medium Enterprises (SMEs), supply chains, and long-term industrial capability beyond a single asset	Prioritize when procurement generates durable industrial and workforce spillovers	ESA industrial policy: ¹⁴² Procurement aims to strengthen European industry's competitiveness, foster SME participation, and build industrial capacity efficiently and economically

Public Sector Role / Decision Drivers	Key Considerations	Decision Logic	Illustrative Cases
Market Creation and Commercialization Support	Potential for the state to catalyze a new market by procuring services or outcomes rather than prescribing a fixed technical solution	Use partnership or service-based procurement when the goal is to stimulate a future commercial market, not only to acquire hardware	JAXA CRD2: ¹⁴³ Program designed to acquire debris-removal technologies while enabling commercial activity and market creation through service specifications
Safety and Sustainability Regulation	Need for operational rules to reduce systemic risks, protect the orbital environment, and ensure long-term domain usability	Tighten requirements when unmanaged risks create externalities for other operators or future missions	FCC 5-year post-mission disposal rule (FCC 22-74): ¹⁴⁴ Reduction of the maximum disposal period of satellites in LEO from 25 years to 5 years after mission completion to mitigate orbital debris risk
Fair, Predictable, and Investable Market Conditions	Whether liability, insurance, and licensing frameworks are proportionate and enable commercial activity without compromising safety	Apply risk-based regulation when uniform rules would distort the market or impose unnecessary costs	UK Space Industry Act / Modeled Insurance Requirement: ¹⁴⁵ Tailored insurance requirements based on mission risk to enable commercial space flight and reduce costs

Public sector assessments remain predominantly qualitative, often supported by multi-expert evaluation processes to reduce ambiguity, distribute accountability, and strengthen the robustness of decisions.



3.2

Private Investors & Financial Institutions

Private investors and financial institutions allocate capital to emerging space technologies when risk-adjusted returns are supported by scalable business models, a credible demand signal, and clear pathways to revenue and exit.

Early-stage companies without demonstrated performance or space heritage can struggle to secure large-scale institutional procurement or later-stage financing. As a result, many rely on seed and early-growth private capital to validate the business model, build traction, and position themselves for larger funding rounds and institutional customers. This reflects the higher burden of proof for technologies that lack operational validation or institutional backing.

Private investors¹⁴⁶ are selective in space not because of technology risk alone, but because revenue realization is often delayed, capital intensity is high, and customer demand is frequently dependent on public-sector adoption. Consequently, investment is concentrated in segments where demand is already visible or can be anchored by institutional customers.¹⁴⁷ This creates a structural bias toward downstream applications, data-driven services, and software-led capabilities, while capital-intensive or infrastructure-heavy technologies face longer funding cycles.

For venture capital, decision-making is driven by growth and exit potential. The focus is on whether a solution can scale rapidly in a large or expanding market and whether the company can capture sufficient market share within a defined timeframe to deliver venture-scale returns. This creates a preference for business models that can convert technical capability into revenue early and scale quickly.

By contrast, financial institutions operate under a fundamentally different risk framework. Banks, private credit providers, export credit agencies, development finance institutions, and sovereign investors prioritize bankability over growth. Their assessment centers on predictable cash flows, contractual certainty, counterparty strength, insurance coverage, and downside protection. Capital is typically deployed only after technologies move beyond proof of concept and are tied to secured demand, institutional customers, or long-term contracts.

Across both investor types, one factor increasingly shaping decision-making is multi-application potential. Technologies that serve both civil and government markets benefit from more stable, diversified demand, often anchored by public-sector procurement. This can strengthen revenue visibility and reduce demand uncertainty, making them more attractive to both growth-oriented and risk-sensitive capital.

However, multi-application characteristics also introduce constraints. Export controls, regulatory exposure, customer concentration, and geopolitical sensitivity can limit market access and complicate scaling strategies. As a result, investment decisions are shaped not only by commercial potential but also by the ability to navigate these constraints while maintaining access to both markets.

Beyond these structural considerations, timing plays a decisive role in capital allocation.

Investors are highly sensitive to market readiness, the reliability of the technology, and the team's ability to execute within a narrow window of opportunity. Even technically mature solutions may struggle to attract capital if regulatory frameworks, procurement pathways, or customer commitments are not sufficiently developed.

As a result, investment decisions are not determined by technological maturity alone but by the degree of alignment among policy

signals, market demand, and commercial execution. Technologies that demonstrate convergence across these dimensions are significantly more likely to attract and sustain private capital. When this alignment is absent, capital remains constrained regardless of the underlying technical potential. Table 23 illustrates the key decision drivers for investment in the space sector.

Table 23: Key Investment Decision Drivers in the Space Sector

Investor Driver	Assessment Focus	Typical Investor Response	Illustrative Case
Commercial Traction & Demand Visibility	Evidence of real customer demand, identifiable buyers, revenue momentum, and transition from demonstration to repeatable business	Invest when clear market pulls or contracted demand exist; defer when demand remains speculative or technology-led	ICEYE growth funding round (2024): ¹⁴⁸ Oversubscribed \$93 million round, supported by more than \$100 million in revenue, with the raise linked to continued demand from allied governments and expanding data and subscription products
Scalability & Market Expansion Potential	Ability to scale across geographies, customer segments, and large addressable markets without being constrained to niche applications	Scale capital when growth is repeatable, and market expansion is credible; limit exposure when scalability is uncertain	EIB financing for Sateliot (2024): ¹⁴⁹ €30 million loan to support 100+ satellite constellations targeting global IoT connectivity to serve over 8 million devices in remote and underserved areas worldwide
Revenue Model Strength and Margin Expansion	Potential for recurring, subscription-based, or infrastructure-like revenue streams with improving margins over time	Invest when business models support recurring and higher-margin revenues; defer when revenues remain episodic or project-based	Intuitive Machines' strategic equity investment (2026): ¹⁵⁰ A \$175 million strategic equity investment led by global institutional investors to support revenue expansion into communications and data-processing networks delivering communications and data services with recurring revenues and higher margins SpaceX (2025–2026): ¹⁵¹ Starlink's subscription-based broadband model reached more than 9 million users globally and reportedly generated 50%–80% of SpaceX's revenues. Reuters reported SpaceX revenue of roughly \$15–16 billion in 2025 and about \$8 billion in EBITDA profit, illustrating how recurring connectivity services can shift a space company from project-based revenues toward infrastructure-like cash flows and margin expansion

Investor Driver	Assessment Focus	Typical Investor Response	Illustrative Case
Multi-Application Advantage & Demand Resilience	Exposure to both commercial and governmental demand enhances revenue stability and downside protection	Overweight when multi-application demand strengthens capabilities; remain cautious when reliant on a single demand segment	ICEYE growth round (2024): ¹⁵² Growth is linked to civil and government demand, strengthening its position as both a commercial and strategic asset
Capital Structure & Financing Sustainability	Alignment between capital needs and financing structure, including a balance between equity, debt, venture debt, and alternative instruments	Finance when capital structure supports growth without excessive fragility; defer or restructure when capital intensity is misaligned	ICEYE extension round (2024): ¹⁵³ \$158 million total raised through a mix of equity and debt from Solidium, BlackRock, and Seraphim, among others
Institutional Validation & Catalytic Financial Support	The presence of credible financial institutions, development banks, or anchor investors reduces perceived execution risk and attracts additional capital	Invest alongside trusted institutions that validate the opportunity; remain selective in the absence of credible anchors	EIB/Satelliot (2024): ¹⁵⁴ Venture-debt financing backed by InvestEU reinforces investor confidence
Strategic Partnership & Monetization Pathways	Ability to unlock adjacent revenue streams through partnerships, downstream services, or cross-sector integration	Invest when capital enables new monetization channels or ecosystem expansion; defer when the company remains too isolated	Tokio Marine–ICEYE (2022): ¹⁵⁵ Strategic investment in ICEYE as part of its Series D round, and the two companies tied the investment to joint development of new insurance products
Liquidity, Governance & Exit Flexibility	Financial resilience, governance quality, and flexibility to pursue restructuring, private ownership, or longer-term capital arrangements	Support restructuring or alternative ownership when it strengthens financial stability and long-term value; avoid when governance or investor alignment is weak	Astra take-private (2024): ¹⁵⁶ Transaction driven by liquidity constraints and long-term investor alignment

3.3 | Corporations & Industrial Actors

Corporations and industrial actors adopt emerging space technologies to strengthen their competitive positions, secure their supply chains, and sustain long-term operational advantages.

Corporations and industrial actors, including system integrators, satellite operators, and downstream service companies, evaluate emerging space technologies through an operational and strategic lens, prioritizing integration, performance, and competitive impact over standalone financial returns. The decision threshold is whether the technology improves the business footprint or prevents competitive loss.

Technologies are adopted when they deliver measurable operational or commercial gains. These gains include enabling differentiated services, reducing operating costs, improving system performance, increasing responsiveness, or unlocking access to new markets. Adoption is driven by impact within existing operations, not novelty. Solutions that generate incremental revenue from current customers or materially improve margins are prioritized.

However, demonstrated value alone is not sufficient to drive adoption. Constraints in supply, integration, and execution often determine whether a technology can be deployed at scale. Supply-chain limitations now directly shape these decisions.¹⁵⁷ Limited access to specialized components, semiconductors, and critical subsystems has shifted priorities toward reliability, control, and operational continuity. As a result, less advanced technologies may be preferred when they reduce dependency risks, diversify sourcing, and ensure stable delivery across the value chain.

To manage these constraints, engagement follows a staged, controlled approach. Corporations typically progress from procurement to pilot projects, partnerships, and, where justified, strategic investment through corporate venture capital. Each step serves as a validation gate, with progression tied to pilot performance, integration costs, alignment with internal roadmaps, and confirmed customer demand.

Within this process, integration is the decisive factor. Technologies must align with existing architectures, meet certification requirements, and deploy without disrupting operations. Qualification timelines, compliance obligations, interoperability constraints, and assurance processes directly shape adoption outcomes. Solutions that minimize integration complexity and certification burden consistently outperform more advanced but less compatible alternatives.

This creates structural tension in industrial decision-making. Protecting existing revenue streams favors incremental adoption, while moving too cautiously increases exposure to obsolescence and competitive displacement. Moving too aggressively, however, can cause integration failures and stranded investments, making the balance between these risks a key determinant of the pace and scale of adoption.

Table 24 presents the main drivers of investment choices among industrial actors.

Table 24: Decision Drivers for Corporations and Industrial Actors in Adopting Emerging Space Technologies

Decision Driver	Assessment Focus	Decision Trigger	Illustrative Example
Strategic Alignment	Fit with product roadmap, priority markets, and growth strategy	Approve or partner when aligned with core strategic direction; defer when outside the roadmap horizon	Lockheed Martin/Terran Orbital: ¹⁵⁸ Acquisition aligned with strategic growth priorities and accelerated execution
Production Scale & Delivery Capacity	Impact on manufacturing throughput, vertical integration, and ability to meet demand	Approve or integrate when capacity and delivery reliability are materially strengthened; defer when scale benefits are marginal	Lockheed Martin/Terran Orbital: ¹⁵⁹ Added high-throughput, manufacturing, and modular production capability
Supply Chain Resilience	Reduction of dependency risks and assurance of continuity in critical components and subsystems	Approve when continuity, replenishment, or supplier control is improved; defer if complexity increases without improved capability	Eutelsat/Airbus OneWeb follow-on order: ¹⁶⁰ Additional satellites secured continuity and replenishment of the constellation
Strategic Fit and Capability Expansion	Ability to fill capability gaps and enhance performance without duplicating existing assets	Approve or partner when the solution expands coverage or capability; defer when overlap is high	Airbus/Synspective: ¹⁶¹ SAR access complemented the existing portfolio, improving revisit times and coverage
Customer Demand & Market Validation	Existing customer base, mission-critical use, and backlog visibility	Approve when demand is proven and mission assurance is credible; defer when demand is uncertain	Lockheed Martin/Terran Orbital: ¹⁶² Strong government and commercial mission track record supported by acquisition

Decision Driver	Assessment Focus	Decision Trigger	Illustrative Example
End-to-End Integration Value	Contribution to integrated offerings across systems, orbits, or services	Approve when the capability strengthens a complete solution stack; defer when integration value is limited	SES/Intelsat: ¹⁶³ Created a multi-orbit, multi-band integrated connectivity offering
Interoperability & Ecosystem Reach	Compatibility with external systems and the ability to participate in broader networks	Approve when interoperability expands market access; defer when locked into proprietary systems	SES Open Orbits: ¹⁶⁴ Open architecture enabled seamless multi-network airline connectivity
Technology & Performance Advantage	The degree to which the technology enhances performance, efficiency, or operational capability	Approve, partner, or invest when performance gains are material; defer when the improvements are incremental	Airbus/Greenerwave: ¹⁶⁵ Flat-panel antennas improved energy efficiency and multi-orbit capability

For corporations and industrial actors, adoption ultimately depends on whether a technology can create measurable value without introducing disproportionate operational risk. Table 25 shows that strategic fit, integration requirements, supply-chain resilience, customer demand, and performance gains are assessed together rather than in isolation. Technologies are therefore most likely to scale when they strengthen the existing business while preserving the flexibility needed to respond to future market and competitive shifts.

04

Conclusion & Strategic Way Forward

Emerging space technologies are becoming essential to the future of exploration, economic growth, resilience, and technological self-sufficiency. Yet technical progress alone will not determine which capabilities achieve meaningful adoption. Their success will depend on whether technological maturity is matched by credible demand, industrial capacity, skilled talent, investment readiness, and an enabling policy environment.¹⁶⁶

The five technology clusters assessed in this report illustrate both the scale of opportunity and the complexity of moving from technical potential to operational deployment. Their development will not follow a uniform path, as each faces distinct market conditions, infrastructure requirements, investment constraints, and regulatory challenges. Progress will therefore depend on coordinated action among governments, industry, investors, research institutions, and the broader innovation ecosystem.¹⁶⁷

The second phase of the initiative is already underway to identify and validate five additional technology priorities to complete the Top 10 portfolio. Through the ongoing survey, expert consultations, and further validation, CSF will broaden the evidence base and capture additional signals across the space economy. This process will ensure that the final portfolio reflects both expert assessment and the priorities of technology developers, operators, investors, policymakers, researchers, and end-users.

The completed Top 10 portfolio will provide a more comprehensive view of the capabilities likely to shape the space economy through 2035. It will also clarify how these technologies reinforce one another, where shared dependencies may constrain progress, and which enabling capabilities

require coordinated development. Rather than treating each technology in isolation, the portfolio will support a more integrated understanding of the systems, markets, and policy conditions needed to enable adoption at scale.

The strategic challenge now extends beyond identifying promising technologies to creating the conditions that enable them to mature and reach the market. CSF can support this transition by convening relevant actors, strengthening visibility into technology and market readiness, enabling regulatory and standards dialogue, and facilitating partnerships among technology developers, investors, operators, and potential customers. It can also help integrate cross-sector capabilities into space applications and identify where space technologies can create value across terrestrial industries.

A central instrument in the next phase of this initiative will be the development of a marketplace platform that connects technology developers, investors, operators, and potential customers. The platform will provide developers with a structured channel to present their capabilities, maturity levels, use cases, funding needs, and partnership opportunities, while enabling investors to assess credible opportunities, compare development pathways, and better understand associated risks. By improving transparency and reducing information asymmetries, the marketplace can strengthen deal flow, clarify demand, and support more informed capital allocation.¹⁶⁸

Ultimately, the objective of this initiative is not simply to identify the technologies most likely to shape the future of space. It is to create the conditions for those technologies to mature, attract investment, strengthen industrial capability, and deliver long-term value. By

linking foresight with market activation, cross-sector engagement, and evidence-based policy dialogue, the framework presented in this report provides a foundation for a more resilient, competitive, and internationally connected space economy.



05

Appendix A: Illustrative Market Signals

Appendix A presents illustrative space-technology startups and investment signals across the five priority technology clusters identified in this report. It captures how emerging companies, financing activity, and commercial capability development have clustered around technologies assessed as strategically significant to the future space economy since 2023.^[b]

The mapping complements the technology assessment by identifying where entrepreneurial activity, investment, and commercial experimentation are already emerging. It also highlights differences in market maturity across the technology clusters. While areas such as AI-enabled analytics, satellite platforms, propulsion, and space communications show clear commercial momentum, others (particularly ISRU and space resources) remain comparatively underrepresented, indicating opportunities for further consultation, targeted scouting, and cross-sector engagement.

The appendix also supports the initiative's broader objective of aligning technology readiness with market readiness. By linking technology clusters to representative companies, investment signals, and potential applications, it provides an initial evidence base for future matchmaking between technology developers and investors through the CSF marketplace. It also highlights opportunities for cross-sector engagement, in which terrestrial capabilities may accelerate technology maturity and expand commercial markets.

The listed companies should therefore be treated as indicative examples rather than a ranking. They provide an initial reference point for further validation through expert review, stakeholder consultation, and broader ecosystem engagement.

^[b] Funding and company data are current as of September 2026. Investment figures are based on publicly announced transactions and the sources cited for each company.

5.1

AI, Autonomy & Robotics

Table 25: Illustrative Market Signals for AI, Autonomy, and Robotics Startups

Illustrative Company	Core Capability	Recent Investment Signal	Strategic Market Signal
Fortastra — United States	Intelligent spacecraft can maneuver, assess conditions, and act to protect space systems	Q4 2025 Seed, \$8M; ¹⁶⁹ primarily VC-backed	Investor interest is converging around autonomy for asset protection, mission assurance, and reduced operational disruption in increasingly congested orbits
HawkEye 360 — United States	RF signal intelligence, geolocation, and characterization for intelligence and government users	Q2 2026 IPO: \$416M gross offering; Q1 2026: additional Series E close of approximately \$23M ¹⁷⁰	Space-derived intelligence and AI-enabled analytics are attracting demand at scale from ministries and security customers
Hadrian — United States	Automated factories and inspection systems for aerospace, governmental, and critical-infrastructure manufacturing	Q3 2026 Series D: \$1.37B; ¹⁷¹ reported valuation approximately \$7.87B ¹⁷²	Manufacturing automation is a cross-sector enabler that can strengthen domestic aerospace production capacity and address skilled-labor bottlenecks
Project Prometheus — United States	AI for the physical economy, including materials design, engine testing, and simulation of complex structures before production	Q2 2026: \$12B financing at a \$41B valuation; follows an initial \$6.2B raise in Q4 2025. ¹⁷³ Jeff Bezos is a co-founder and investor	Very large AI/physical-systems funding signals investor appetite for platforms that compress engineering cycles; space relevance should be further validated
Digantara — India	Space surveillance and intelligence platform turning raw tracking data into decision-ready space-domain awareness	Q4 2025 Series B, \$50M; ¹⁷⁴ led by Reliance Industries	SSA/STM analytics are becoming investable as governments and operators require actionable intelligence for safety, resilience, and government applications
Stardetect — China	Space-based edge computing for intelligent satellites	Q4 2025 Series A, \$14M ¹⁷⁵	Edge processing supports on-board autonomy, reduces dependence on downlink, and enables faster data exploitation

5.2

In-Space and On-Orbit Servicing, Assembly & Manufacturing

Table 26: Illustrative Market Signals for ISAM and OSAM Startups

Illustrative Company	Core Capability	Recent Investment Signal	Strategic Market Signal
Catalyx Space — India	Autonomous space labs and reusable capsules for deploying experiments and manufacturing in orbit	Q4 2025 Seed: \$5.4M; Q1 2025 pre-Seed: \$1.7M ¹⁷⁶	Early-stage capital is flowing into reusable in-orbit platforms, linking ISAM, microgravity R&D, and government-oriented orbital infrastructure
Infinite Orbits — France	In-orbit servicers for GEO satellite operators, including inspection and servicing-oriented capabilities	Q4 2025 Series B, €40M; ¹⁷⁷ European Innovation Council Fund involved	European financing reflects the strategic relevance of in-orbit servicing for space sovereignty, asset life extension, and resilient orbital infrastructure
Varda — United States	In-space manufacturing and re-entry infrastructure for products made in orbit and returned to Earth	Q1 2026 Series D: approximately \$250M at a reported ~\$1.6B valuation; ¹⁷⁸ Q3 2025 Series C: \$187M; ¹⁷⁹ Q2 2024 Series B: \$90M ¹⁸⁰	Varda illustrates the transition from isolated microgravity experiments toward commercial orbital manufacturing and returns logistics

5.3

Advanced Propulsion and Space Power Systems

Table 27: Illustrative Market Signals for Advanced Propulsion and Space Power Systems Startups

Illustrative Company	Core Capability	Recent Investment Signal	Strategic Market Signal
Stoke Space — United States	Fully reusable rockets designed for on-demand access to orbit	Q3 2026 Series E: initial closing of \$1.0B, bringing total capital raised to \$2.3B; ¹⁸¹ follows a \$860M Series D+ in Q1 2026 ¹⁸²	Large late-stage financing confirms strong investor demand for reusable launch and responsive access as an enabling layer for the space economy
Space Pioneer — China	Environment-friendly rocket propulsion and medium-to-large launch vehicles	Q4 2025 Series D+, \$350M; ¹⁸³ Q2 2024 Series C, \$207M ¹⁸⁴	Chinese launch and propulsion investment reflects national ambition, commercial launch scale-up, and strategic autonomy in access to space
Antares Industries — United States	Fission microreactors for strategic energy across Earth, space, and underwater critical missions	Q3 2026 Series C: \$470M, comprising \$370M in equity and \$100M in debt; ¹⁸⁵ follows a \$96M Series B in Q4 2025 ¹⁸⁶	Advanced power is emerging as a strategic subsystem for long-duration, high-energy, and government-relevant missions
Relativity Space — United States	3D-printed rockets and manufacturing-first launch architecture	Q3 2026 implied valuation: \$2.81B; follows a \$6.03 Series F valuation in Q4 2023 ¹⁸⁷	Additive manufacturing and production simplification remain relevant to lowering cost, reducing parts complexity, and shortening launch-vehicle development timelines

5.4

In-Situ Resource Utilization & Space Resources

Table 28: Illustrative Market Signals for ISRU and Space Resources Startups

Illustrative Company	Core Capability	Recent Investment Signal	Strategic Market Signal
No direct ISRU startup was identified in the dataset used for this appendix as of September 2026.	ISRU, space resources, lunar mining, excavation, oxygen extraction, water prospecting, resource processing, and mining robotics.	No direct funding signal was identified in the dataset used for this appendix as of September 2026.	ISRU remains an emerging market with limited visible commercial and investment signals as of September 2026. Market development is constrained by early technology maturity, uncertain near-term demand, and unresolved legal and governance questions ¹⁸⁸ surrounding space resource extraction and use.

5.5

Space Communications and On-Orbit Data Infrastructure

Table 29: Illustrative Market Signals for Space Communications and On-Orbit Data Infrastructure Startups

Illustrative Company	Core Capability	Recent Investment Signal	Strategic Market Signal
Starcloud — United States	Space-based AI computing infrastructure: directory notes the launch of an NVIDIA H100 GPU in space	Q3 2026 Series A extension: \$250M at a reported \$2.3B valuation; ¹⁸⁹ follows the Q1 2026 \$170M Series A ¹⁹⁰	Investor interest is expanding from communications into orbital data centers and compute infrastructure as terrestrial data-center constraints increase
Transcelestial — Singapore	Space laser networks connecting Earth to deep space and supporting satellite-to-ground optical communications	Q4 2025: additional \$9.7M financing close, bringing total funding to \$34.7M; ¹⁹¹ follows a Q2 2025 financing round that brought total investment to \$30.7M ¹⁹²	Optical communications are positioned as enabling infrastructure for secure, high-throughput, and lower-jamming satellite connectivity

Appendix B contains the factsheets for each of the top five emerging space technologies identified through Phase I of the CSF Space Technologies Flagship Initiative. The factsheets offer a more concise, accessible snapshot of the key findings of the ‘Pioneering the Future: Space Technologies Poised to Revolutionize Exploration and Economy by 2035’ report. Their purpose is to help policymakers, investors, industry leaders, decision-makers, researchers, and technology developers quickly identify the relevance, readiness, and investment potential of each priority technology.

Each factsheet summarizes the strategic value proposition, key applications, cross-sector capabilities, readiness levels, market opportunities, development barriers, adoption enablers, and investment outlook of the respective top five technology clusters identified through expert consultation, survey results, and workshop discussions. The factsheets complement the technology deep dives in the full report by bridging analysis and action. They translate the report’s findings into a decision-support output to help stakeholders identify where space technologies are maturing, where bottlenecks remain, where investment confidence can be strengthened, and where collaboration across public, private, and research ecosystems can accelerate market deployment.

6.1 | AI, Autonomy & Robotics

AI, Autonomy & Robotics enable space systems to sense, interpret, decide, and act with reduced ground control. They support onboard processing, autonomous operations, robotic inspection and servicing, anomaly detection, predictive maintenance, mission optimization, and space sustainability analytics.

Strategic Value Proposition



Enables scalable satellite constellations, deep-space missions, ISAM and OSAM, and robotic operations.



Reduces latency, downlink burden, and dependence on continuous ground control.



Improves mission safety, responsiveness, and resource optimization.



Strengthens mission resilience, cost-efficiency, and operational performance across space systems.

Key Applications

01

EO analytics and onboard data triage.

02

Autonomous spacecraft operations and mission management.

03

Anomaly detection and predictive maintenance.

04

Constellation coordination and swarm autonomy.

05

Robotic inspection, servicing, assembly, and manufacturing.

06

SSA and collision-avoidance support.

07

Deep-space autonomy and surface robotics.

Cross-Cutting Capabilities

- Digital twins, simulation, and engineering support.
- Verification, validation, and mission assurance tools.
- Spillovers for logistics, mining, infrastructure monitoring, and disaster response.
- Multi-application relevance across civil, commercial, and national applications.

Readiness Assessment

TRL

5-7*

Validation to demonstration in relevant or operational environments.

MRL

4-6

Capability proven in production-relevant environments.

Mkt-RL

5-7

Early commercial adoption emerging for select applications.



Note: Software-heavy applications are closer to adoption, while robotics, onboard edge AI, ISAM and OSAM, and deep-space autonomy require more flight heritage and validation. *The TRL range is indicative only, as maturity varies significantly across sub-capabilities, with individual assessments ranging from TRL 4-6 to TRL 6-8.

Market Opportunity



Macro AI tailwind: **approximately 38% CAGR (2023-2033)**.



Distributed across multiple market segments.



Priority segments include:

- EO and geospatial intelligence.
- Mission operations software.
- SSA and collision-avoidance analytics.
- Onboard edge AI and autonomy stacks.
- Robotics, ISAM, and swarm systems.



Development Barriers

- Limited availability of space-grade computing and onboard power.
- Fragmented datasets and insufficient validation environments.
- High costs for qualification, certification, and flight demonstration.
- Cybersecurity exposure and export-control constraints.
- Challenges in explainability, liability, accountability, and operational trust for mission-critical decisions.

Adoption Enablers

In-orbit testbeds and demonstration missions.

Shared datasets, digital twins, and simulation platforms.

Verification, validation, explainability, cybersecurity, and mission assurance frameworks.

Anchor procurement, public-sector co-funding, and regulatory clarity.

Partnerships with AI, robotics, semiconductor, and advanced manufacturing actors.



Investment Outlook

Near-term investability:

Data fusion, EO analytics, SSA, mission operations, and anomaly detection.

Medium-term opportunities:

Onboard edge AI, autonomy stacks, and predictive maintenance.

Long-term strategic bets:

Robotics, ISAM and OSAM, swarm systems, and deep-space autonomy.



Note: Software-heavy models may offer shorter payback cycles, while hardware-intensive systems require stronger de-risking through demonstrations, procurement, and flight heritage.

6.2

In-Space and On-Orbit Servicing, Assembly & Manufacturing

ISAM and OSAM enable the assembly, integration, servicing, upgrading, and manufacturing of space systems after launch. This shifts space operations from a launch-and-replace model toward serviceable, modular, and reusable orbital infrastructure, while laying the foundation for larger platforms, cislunar logistics, and future in-space industrial activity.

Strategic Value Proposition



Extends the life, resilience, and utility of satellites and orbital infrastructure.



Reduces replacement launches through in-orbit inspection, servicing, repair, repositioning, and upgrades.



Supports space sustainability through servicing, disposal, and debris-removal capabilities.



Establishes the foundation for future deep-space and large-scale in-space infrastructure.

Key Applications

01

Satellite life extension.

02

Inspection and anomaly assessment.

03

Rendezvous, proximity operations, and docking.

04

Refueling, tugging, and repositioning.

05

Robotic capture and active debris removal.

06

Logistics and disposal services.

Cross-Cutting Capabilities

- Space sustainability and debris mitigation.
- Satcom and infrastructure resilience.
- Exploration, cislunar platforms & deep-space logistics.
- Spillovers in remote maintenance, offshore energy, aviation, mining automation, and robotics.
- Applications across the other priority emerging space technologies.

Readiness Assessment — Highly uneven across subsegments

TRL

4-9

Selected capabilities demonstrated.

MRL

3-8

Varied production maturity across subsystems and missions.

Mkt-RL

2-6

Early commercial adoption; strongest for life extension, inspection, and logistics support.

Note: Readiness varies widely across ISAM/OSAM capabilities. Life-extension services drive the upper end, while refueling, repair, modular upgrades, large-scale assembly, and in-space manufacturing remain less mature.

Market Opportunity



Estimated growth: **\$2.7B (2024) to \$5.0-8.0B (2030-2034).**



Long-term upside linked to reusable space infrastructure, satellite servicing, in-space logistics, refueling, and in-space manufacturing.



Priority segments include:

- Life extension
- Inspection
- Refueling
- Relocation
- Anomaly recovery
- Manufacturing
- Disposal support
- In-space logistics

Market estimates are directional due to variations in scope and definitions across ISAM and OSAM services and activities.



Development Barriers

- Complex proximity operations and docking risks.
- Unprepared targets for servicing.
- Lack of standardized interfaces and modular spacecraft design.
- High CAPEX, qualification costs, and limited in-space testing.
- Regulatory ambiguity, liability allocation, insurance uncertainty, cybersecurity, and multi-application sensitivities.
- Limited repeatable demand and uncertain revenue models for services.

Adoption Enablers

Anchor procurement, service contracts, and public-private co-funding.

Standardized interfaces and modular spacecraft architectures.

Shared testbeds, in-space sandboxes, and pilot missions.

Transparent safety standards, regulatory pathways, and insurance.

Frameworks for proximity operations, authorization, liability, and responsible behavior in orbit.



Investment Outlook

Near-term investability:

Life extension, inspection, relocation, anomaly recovery, and disposal support.

Medium-term opportunities:

Refueling, modular upgrades, and prepared-satellite servicing.

Long-term strategic bets:

Large-scale assembly, in-space manufacturing, and cislunar infrastructure.

Note: National demands can act as early anchor markets; bankability depends on revenue-linked use cases, repeated demonstrations, and clearer regulatory pathways.

6.3

Advanced Propulsion and Space Power Systems (AP&SPS)

AP&SPS enable spacecraft mobility, endurance, maneuverability, long-duration operations, and future cislunar and deep-space infrastructure. The cluster includes electric, chemical, and green propulsion, high-power propulsion concepts, power generation, energy storage, power management, and SNP&P.

Strategic Value Proposition



Improves mission mobility, endurance, and flexibility.



Supports orbit-raising, station-keeping, collision avoidance, and deorbiting.



Enables high-power payloads, long-duration operations, cislunar logistics, and deep-space missions.



Enhances resilience, energy availability, maneuverability, and mission lifetime.

Key Applications

01

Orbit-raising, station-keeping, collision avoidance, and deorbiting.

02

Cislunar logistics, deep-space transfer, and high-energy mobility.

03

Surface power, high-power payloads, and long-duration operations.

04

Servicing, tugging, and responsive-space missions.

05

SNP&P for long-duration, high-energy, and surface applications.

Cross-Cutting Capabilities

AI/autonomy, ISAM, space logistics, and lunar/Martian infrastructure.

Communications, exploration, and deep-space missions.

Energy systems, hydrogen, semiconductors, and advanced manufacturing.

Spillovers in microgrids, electric mobility, mining automation, and power safety governance.

Readiness Assessment — Overall uneven maturity across propulsion and power

TRL

3-9

Mature for chemical/electric propulsion, solar arrays, batteries, and power management; lower for high-power propulsion, advanced storage, in-orbit refueling, and SNP&P.

MRL

2-9

Strong for established propulsion and power systems; lower for high-power, SNP&P, and long-duration technologies.

Mkt-RL

2-9

Strongest demand for electric propulsion, satellite power systems, and select green propulsion applications.

Note: Readiness varies widely across AP&SPS technologies. Mature chemical and electric propulsion and established power systems drive the upper end, while nuclear propulsion, fission power, and other emerging high-power architectures remain less mature.

Market Opportunity



\$10.2B (2024) to \$20.0B (2030) at 11.9% CAGR.



Demand is driven by larger constellations, high-power payloads, maneuverable spacecraft, cislunar activity, deep-space missions, and surface infrastructure.



Priority segments include:

- Electric and green propulsion
- High-power propulsion
- Power generation
- Energy storage
- Power management
- SNP&P

Note: Market definitions vary; figures are indicative.



Development Barriers

High testing costs and lengthy qualification timelines.

Complex mass, efficiency, power, & thermal trade-offs.

Limited demonstration opportunities for high-power and SNP&P.

Degradation due to harsh environments.

Supply-chain constraints for specialized components and advanced materials.

Regulatory, safety, licensing, and public-acceptance challenges for SNP&P technologies.

Adoption Enablers

Shared qualification frameworks, test infrastructure, and in-space demonstrations.

Standardized interfaces, modular architectures, and scalable propulsion platforms.

Clearer regulatory pathways for high-power and SNP&P.

Cross-sector partnerships across energy, nuclear, hydrogen, aviation, automotive, semiconductors, materials, and advanced manufacturing.



Investment Outlook

Strongest near-term cases:

Electric and smallsat propulsion, deployable solar arrays, batteries, power management, and select green propulsion systems.

Longer-term strategic bets:

SNP&P, cislunar logistics, deep-space transportation, and surface power infrastructure.

Note: Government anchors and flight heritage will reduce risk.

6.4

In-Situ Resource Utilization (ISRU) & Space Resources

ISRU refers to the prospecting, extraction, processing, storage, and use of materials found beyond Earth to support space operations through propellant production, life support, shielding, construction, and industrial feedstocks. ISRU reduces dependence on Earth-launched supplies, enabling sustainable operations.

Strategic Value Proposition

-  **Reduces** dependence on Earth-launched supplies by enabling local resource use.
-  **Supports** sustained lunar, cislunar, and future Martian operations.
-  **Provides** propellant, life-support resources, construction materials, and radiation shielding.
-  **Establishes** the foundation for future off-Earth industries and space economies.

Key Applications

- 01 Lunar resource prospecting & mapping, drilling, excavation, and regolith handling.
- 02 Long-duration lunar, cislunar, and Mars missions.
- 03 Volatile detection, water-ice mapping, and water and oxygen extraction.
- 04 Propellant production and fuel depots.
- 05 Resource assessment for asteroids and other non-terrestrial bodies.
- 06 Radiation shielding and surface infrastructure.
- 07 Life-support resources and habitat consumables.
- 08 Construction materials and in-situ manufacturing.

Cross-Cutting Capabilities

- Mining, robotics, autonomy, energy systems, hydrogen, cryogenics, advanced materials, construction, digital twins, insurance, and science diplomacy.
- Spillovers in autonomous mining, off-grid power, hydrogen systems, water recovery, low-carbon construction, hazardous-environment robotics, and frontier-infrastructure finance.

Readiness Assessment — Overall low-to-moderate and highly uneven across subsegments

TRL

3-8

Some subsystem demonstrations, but end-to-end systems are still early-stage.

MRL

2-6

Limited production and operational maturity.

Mkt-RL

2-5

Demand signals exist, but commercial markets are not yet established.

Note: Prospecting and resource-characterization capabilities sit toward the upper end; integrated extraction, processing, propellant production, and operational utilization remain toward the lower end.

Market Opportunity

-  Pre-commercial with widely varying estimates.
-  Space mining: **\$1.90B (2024) to \$5.02B (2030) at 17.6% CAGR.**
-  ISRU-specific: **\$2.80B (2025) to \$9.40B (2034) at 14.4% CAGR.**

Figures are directional and dependent on market definitions, mission cadence, anchor demand, and the pace of lunar and cislunar infrastructure development.



Development Barriers

- Early-stage extraction and processing technologies.
- Limited lunar surface access and constrained in-situ testing opportunities.
- End-to-end demonstrations remain limited.
- High infrastructure costs and long development timelines.
- Evolving regulatory frameworks for resource rights, access, safety, liability, and benefit-sharing.
- Uncertain revenue models and limited near-term anchor demand.

Adoption Enablers

Government anchor demand and procurement.

Current lunar programs are driving sustained demonstrations and interoperability.

Shared lunar analogue facilities and testbeds.

Standards for regolith simulants and resource characterization.

End-to-end pilot missions for excavation, processing, storage, and utilization.

Anchor customers for key logistics services.



Investment Outlook

- Near-term investability:** Mapping, drilling, delivery, integration, ISRU subsystems.
- Medium-term opportunities:** Oxygen extraction, water-ice validation, autonomous excavation, regolith processing, and pilot-scale production.
- Long-term strategic bets:** Propellant production, fuel depots, large-scale manufacturing, construction materials, and resource markets.

Note: Strong programmatic relevance and high cross-cutting potential, but public exploration programs are likely to be the first anchor customers. Commercial bankability will depend on repeated demonstrations, clear demand, infrastructure build-out and greater legal certainty.

6.5

Space Communications and On-Orbit Data Infrastructure (SC&ODI)

SC&ODI refers to the connectivity, networking, processing, storage, and security layers that enable information exchange across orbital and terrestrial networks. It includes satellite and optical communications, inter-satellite links, multi-orbit networking, onboard processing, edge computing, secure data relay, and space data infrastructures.

Strategic Value Proposition



Enables resilient, secure, low-latency connectivity across orbital and terrestrial networks.



Supports broadband, encrypted communications, EO data relay, and autonomous operations.



Serves as the digital backbone of the future space economy.



Unlocks inter-satellite routing, multi-orbit networks and distributed data pathways.

Key Applications

01

Satellite broadband and direct-to-device connectivity.

02

Secure government and encrypted communications.

03

Real-time EO data relay and cloud-integrated ground services.

04

Multi-orbit optical intersatellite networks.

05

Autonomous spacecraft coordination and edge AI.

06

Cislunar communications, secure data relay, and quantum-ready networks.

Cross-Cutting Capabilities

- Telecom, 5G/6G, cloud, and edge AI.
- Photonics, cybersecurity, and secure digital infrastructure.
- EO, autonomous systems, and encrypted networks.
- Spillover in rural connectivity, disaster response, smart infrastructure, and digital resilience.

Readiness Assessment — Overall medium-high, with substantial variation across sub-capabilities

TRL

3-9

Mature satcom, ground services, and data relay; lower for optical networking, autonomous mesh routing, and orbital computing.

MRL

2-9

Strong for satcom hardware and ground systems; improving for optical terminals, software-defined payloads, and advanced networking.

Mkt-RL

2-9

Strong commercial demand for secure optical satcom, data relay, and cloud-integrated ground services.

Note: Established satcom and ground services drive the upper end; future 6G integration, distributed orbital computing, space-based data centers, and other emerging network layers drive the lower end.

Market Opportunity



Global satcom: **\$107.4B (2026) to \$223.1B (2033) at 11.0% CAGR.**



Small satcom: **\$5.95B (2025) to \$18.34B (2030).**



Additional growth from optical communications and orbital data infrastructure.

Note: Estimates are indicative and vary by market scope (e.g., satcom, data relay, optical communications, ground services, edge processing, and orbital computing).



Development Barriers

- Spectrum constraints and regulatory delays.
- Interoperability gaps and fragmented standards.
- Developing economic viability for orbital data centers.
- Orbital congestion, debris, and collision exposure.
- Optical-link weather sensitivity and infrastructure needs.
- Security, encryption, data-sovereignty, and resilience requirements for government and critical-infrastructure users.
- Contested-space threats such as jamming and cyberattacks.

Adoption Enablers

Streamlining spectrum and licensing pathways.

Developing interoperability standards.

Integrating orbital sustainability by design.

Standardized Multi-orbit optical networks.

Cybersecurity by design and resilience standards.

Ground-to-cloud integration driven by anchor demand.



Investment Outlook

Near-term investability:

- Satcom, secure communications, optical networking, software-defined payloads, cloud-integrated ground systems, and data-relay services.
- Strong interest in secure communications, software-defined payloads, and edge processing.

Medium-term opportunities:

Inter-satellite networking, multi-orbit routing, edge processing, cislunar communications, and autonomous network management.

Risk outlook:

Regulation, market concentration, cybersecurity, and speculative orbital computing models.

Note: National demands, disaster response, and connectivity provide anchor demand.

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08

Endnotes

1. George Martin, *NewSpace: The Emerging Commercial Space Industry* (Moffett Field, CA: NASA Ames Research Center, 2015), https://www.earthdata.nasa.gov/s3fs-public/2023-11/newspace_nasa.pdf.
2. George Martin, “NewSpace: The Emerging Commercial Space Industry,” conference paper, February 22, 2017, NASA Technical Reports Server, <https://ntrs.nasa.gov/citations/20170001766>.
3. William W. Baber and Aija Ojala, “New Space Era: Characteristics of the New Space Industry Landscape,” in *Space Business*, ed. Aija Ojala and William W. Baber (Singapore: Springer, 2024), 3–26, https://doi.org/10.1007/978-981-97-3430-6_1.
4. World Economic Forum and McKinsey & Company, *Space: The \$1.8 Trillion Opportunity for Global Economic Growth* (Geneva: World Economic Forum, 2024), <https://www.weforum.org/publications/space-the-1-8-trillion-opportunity-for-global-economic-growth/>.
5. BryceTech, “BryceTech,” <https://brycetechnology.com/>.
6. King Abdullah University of Science and Technology, “KAUST,” <https://www.kaust.edu.sa/en/>.
7. The European House – Ambrosetti, “The European House – Ambrosetti,” <https://www.ambrosetti.eu/en/>.
8. World Economic Forum and McKinsey & Company, *Space: The \$1.8 Trillion Opportunity for Global Economic Growth* (Geneva: World Economic Forum, 2024), <https://www.weforum.org/publications/space-the-1-8-trillion-opportunity-for-global-economic-growth/>.
9. Mija Aleksandraviciute, Stephen Michael Impink, and Robert Seamans, “Industrial Policy for the Final Frontier: Governing Growth in the Emerging Space Economy,” Brookings Institution, September 23, 2025, <https://www.brookings.edu/articles/industrial-policy-for-the-final-frontier-governing-growth-in-the-emerging-space-economy/>.
10. United Nations Economic and Social Council, Global Cooperation in Science, Technology and Innovation for Development: Report of the Secretary-General, E/CN.16/2024/3 (Geneva: United Nations, 2024), https://unctad.org/system/files/official-document/ecn162024d3_en.pdf.
11. “Strategic Space Assets: National Perspectives and Importance,” *New Space Economy*, December 27, 2024, <https://newspaceeconomy.ca/2024/12/27/strategic-space-assets-national-perspectives-and-importance/>.
12. World Economic Forum and Centre for Space Futures, *Clear Orbit, Secure Future: A Call to Action on Space Debris* (Geneva: World Economic Forum, 2026), <https://www.weforum.org/publications/clear-orbit-secure-future-a-call-to-action-on-space-debris/>.
13. Simone D’Amico, “Space,” *Stanford Emerging Technology Review*, 2025, <https://setr.stanford.edu/technology/space/2025>.
14. Michał Bączny, Koen Frenken, Matthijs B. Punt, and Iris Wanzenböck, “International Alliances and Technology Diffusion: A Worldwide Analysis of Adoption of Energy, Railway and Satellite Technologies,” *PLOS Sustainability and Transformation* 3, no. 6 (2024): e0000112, <https://doi.org/10.1371/journal.pstr.0000112>.
15. Aleksandraviciute, Impink, and Seamans, “Industrial Policy for the Final Frontier,” <https://www.brookings.edu/articles/industrial-policy-for-the-final-frontier-governing-growth-in-the-emerging-space-economy/>.

16. Caitlin Rice, Jill Taylor, Jennifer Widom, and Amy Zegart, "Space," Stanford Emerging Technology Review, February 7, 2025, <https://setr.stanford.edu/technology/space/2025>.

17. New Space Economy, "Strategic Space Assets: National Perspectives and Importance," December 27, 2024, <https://newspaceeconomy.ca/2024/12/27/strategic-space-assets-national-perspectives-and-importance/>.

18. European Space Agency Space Solutions, Artificial Intelligence for Space: Use Cases and Commercial Opportunities (2023), <https://commercialisation.esa.int/wp-content/uploads/2023/04/Artificial-Intelligence-for-Space-MiniReport-230420.pdf>.

19. National Aeronautics and Space Administration, Artificial Intelligence (2026), <https://www.nasa.gov/artificial-intelligence/>.

20. European Space Agency, "Introducing Phsat-2," n.d., https://www.esa.int/Applications/Observing_the_Earth/Phsat-2/Introducing_Phsat-2.

21. James Trailie, "How OSIRIS-REx Will Steer Itself to Sample an Asteroid," NASA Scientific Visualization Studio, March 9, 2020, <https://svs.gsfc.nasa.gov/13555>.

22. William Steigerwald, "Bennu's Boulders Shine as Beacons for NASA's OSIRIS-REx," NASA, March 9, 2020, <https://www.nasa.gov/missions/bennus-boulders-shine-as-beacons-for-nasas-osiris-rex/>.

23. Starfish Space, "The Otter," n.d., <https://www.starfishspace.com/the-otter/>.

24. European Space Agency, "Artificial Intelligence for Space," https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/Artificial_intelligence_in_space.

25. European Space Agency, "Artificial Intelligence for Space."

26. National Aeronautics and Space Administration, "Distributed Spacecraft Autonomy (DSA)," last updated June 30, 2025, [https://www.nasa.gov/game-changing-development-projects/distributed-](https://www.nasa.gov/game-changing-development-projects/distributed-spacecraft-autonomy-dsa/)

[ed-spacecraft-autonomy-dsa/](https://www.nasa.gov/game-changing-development-projects/distributed-spacecraft-autonomy-dsa/).

27. Gianine Figliozzi, "NASA Demonstrates Software 'Brains' Shared across Satellite Swarms," NASA, February 4, 2025, <https://www.nasa.gov/centers-and-facilities/ames/nasa-demonstrates-software-brains-shared-across-satellite-swarms/>.

28. European Space Agency, "Artificial Intelligence in Space," last updated August 3, 2023, https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/Artificial_intelligence_in_space.

29. European Space Agency Space Solutions, *Artificial Intelligence for Space*, https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/Artificial_intelligence_in_space/.

30. EU Space Surveillance and Tracking, "EU Space Surveillance and Tracking," n.d., <https://www.eusst.eu/>.

31. Australian Space Agency, "Exploring Space with Australian Resources Ingenuity," n.d., <https://www.space.gov.au/exploring-space-australian-resources-ingenuity>.

32. UN Trade and Development (UNCTAD), "AI Market Projected to Hit \$4.8 Trillion by 2033, Emerging as Dominant Frontier Technology," April 7, 2025, <https://unctad.org/news/ai-market-projected-hit-48-trillion-2033-emerging-dominant-frontier-technology>.

33. National Science and Technology Council, In-Space Servicing, Assembly, and Manufacturing National Strategy (Washington, DC: Executive Office of the President, 2022), <https://csps.aerospace.org/sites/default/files/2022-05/Nat%20Space%20Servicing%20Strategy%20Apr22.pdf>.

34. National Science and Technology Council, *In-Space Servicing, Assembly, and Manufacturing National Strategy*, <https://space.commerce.gov/national-strategy-for-in-space-servicing-assembly-and-manufacturing-released/>.

35. U.S. Government Accountability Office, In-Space Servicing, Assembly, and Manufacturing: Benefits, Challenges, and

Policy Options, GAO-25-107555 (Washington, DC: U.S. Government Accountability Office, 2025), <https://www.gao.gov/products/gao-25-107555>.

36. Press Information Bureau, Government of India, “SpaDeX Mission: Revolutionising Space Exploration,” January 16, 2025, <https://www.pib.gov.in/PressReleaseDetailm.aspx?PRID=2093369>.

37. Victoria Samson, Russian Military and Intelligence Rendezvous and Proximity Operations Fact Sheet (Secure World Foundation, June 12, 2026), <https://www.swfound.org/publications-and-reports/russian-military-and-intelligence-rendezvous-and-proximity-operations-fact-sheet>.

38. SpaceLogistics, Mission Extension Vehicle (MEV): Award-Winning Satellite-Life-Extension Servicing Vehicle (2021), <https://www.northropgrumman.com/wp-content/uploads/Mission-Extension-Vehicle-MEV-fact-sheet.pdf>.

39. Northrop Grumman, “SpaceLogistics,” n.d., <https://www.northropgrumman.com/what-we-do/space/space-logistics-services>.

40. Xinhua, “China Launches Test Satellite for Orbital Refueling,” State Council of the People’s Republic of China, January 7, 2025, https://english.www.gov.cn/news/202501/07/content_WS677c6feec6d-0868f4e8ee8fa.html.

41. European Space Agency (ESA), “ESA to Build First In-Orbit Servicing Mission with D-Orbit,” October 14, 2024, https://www.esa.int/Space_Safety/ESA_to_build_first_in-orbit_servicing_mission_with_D-Orbit.

42. Japan Aerospace Exploration Agency, “CRD2 Phase I / ADRAS-J Update: Fly-around Observation Images of Space Debris Released,” July 30, 2024, https://global.jaxa.jp/press/2024/07/20240730-1_e.html.

43. European Space Agency, “ESA Commissions World’s First Space Debris Removal,” press release no.23-2019, December 9, 2019, [\[sions_world_s_first_space_debris_removal\]\(https://www.esa.int/Newsroom/Press_Releases/ESA_commissions_world_s_first_space_debris_removal\).](https://www.esa.int/Newsroom/Press_Releases/ESA_commis-</p></div><div data-bbox=)

44. Orbit Fab, “RAFTI™,” n.d., <https://www.orbitfab.com/rafti/>.

45. Northrop Grumman, “Northrop Grumman Selected for In-Space Demonstration of Refueling Technologies,” April 2, 2025, <https://news.northropgrumman.com/satellites/northrop-grumman-selected-for-in-space-demonstration-of-refueling-technologies>.

46. “NASA to Discontinue \$2 Billion Satellite Servicing Project on Higher Costs, Schedule Delays,” Reuters, March 1, 2024, <https://www.reuters.com/technology/space/nasa-discontinue-2-billion-satellite-servicing-project-higher-costs-schedule-2024-03-01/>.

47. Redwire, “Additive Manufacturing Facility: 3D Printing the Future in Space,” March 20, 2019, <https://rdw.com/newsroom/2019-3-28-additive-manufacturing-facility-3d-printing-the-future-in-space/>.

48. Orbit Fab, “RAFTI™,” n.d., <https://www.orbitfab.com/rafti/>.

49. United States Space Force, “Space Threat Fact Sheet,” September 8, 2025, <https://www.spaceforce.mil/About-Us/Fact-Sheets/Fact-Sheet-Display/Article/4297159/space-threat-fact-sheet/>.

50. U.S. Government Accountability Office, *In-Space Servicing, Assembly, and Manufacturing*. <https://www.gao.gov/products/gao-25-107555>.

51. National Aeronautics and Space Administration, “On-Orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1),” last updated March 23, 2026, <https://www.nasa.gov/mission/on-orbit-servicing-assembly-and-manufacturing-1/>.

52. MarketsandMarkets, On-Orbit Satellite Servicing Market by Service, End User, Orbit, Type and Region: Global Forecast to 2030, report no. AS 8657 (May 2023), <https://www.marketsandmarkets.com/Market-Reports/on-orbit-satellite-servicing-market-206789424.html>.

53. Global Market Insights, On-Orbit

Satellite Servicing Market Size, Share, 2025–2034, report no. GMI12698 (December 2024), <https://www.gminsights.com/industry-analysis/on-orbit-satellite-servicing-market>.

54. Precedence Research, On-Orbit Satellite Servicing Market Size to Hit USD 12.60 Billion by 2035, report no. 5463, updated January 15, 2026, <https://www.precedenceresearch.com/on-orbit-satellite-servicing-market>.

55. Strategic Market Research, In-Space Manufacturing Market Size and Share Report, 2030, report no.38027640 (October 2025), <https://www.strategic-marketresearch.com/market-report/in-space-manufacturing-market>.

56. WiseGuy Reports, In-Space Manufacturing, Servicing, and Transportation Market Size, 2035, WGR552089 (June 2026), <https://www.wiseguyreports.com/reports/in-space-manufacturing-servicing-transportation-market>.

57. European Space Agency (ESA), “BepiColombo Begins Mercury Arrival with MTM Separation Success,” September 7, 2026., https://www.esa.int/Enabling_Support/Operations/BepiColombo_begins_Mercury_arrival_with_MTM_separation_success?ref=fomoera.com.

58. Rohit Shastry et al., “12-kW Advanced Electric Propulsion System Hall Current Thruster Development and Qualification Status,” conference paper, 38th International Electric Propulsion Conference, Toulouse, France, June 23–28, 2024, NASA Technical Reports Server, document ID 20240006249, <https://ntrs.nasa.gov/api/citations/20240006249/downloads/AEPS%20Status%20IEPC%202024%20v7.pdf>.

59. National Aeronautics and Space Administration, “Fission Surface Power,” last updated September 8, 2025, <https://www.nasa.gov/exploration-systems-development-mission-directorate/fission-surface-power/>.

60. National Aeronautics and Space Administration, “NASA TechPort,” <https://techport.nasa.gov/projects/105665>.

61. Redwire, Roll Out Solar Array (ROSA) Flysheet (2025), <https://rdw.com/wp-content/uploads/2023/06/redwire-roll-out-solar-array-flysheet.pdf>.

62. MarketsandMarkets, Space Propulsion Market (2026), <https://www.marketsandmarkets.com/Market-Reports/space-propulsion-market-118742255.html>.

63. MarketsandMarkets, Satellite Propulsion Market (2026), <https://www.marketsandmarkets.com/Market-Reports/satellite-propulsion-market-205639295.html>.

64. Grand View Research, Satellite Propulsion System Market Size, Share, and Trends Analysis Report (2025), <https://www.grandviewresearch.com/industry-analysis/satellite-propulsion-system-market-report>.

65. National Aeronautics and Space Administration, Fission Surface Power, last updated September 8, 2025, <https://www.nasa.gov/exploration-systems-development-mission-directorate/fission-surface-power/>.

66. Matthew Hancock et al., “The Polar Resources Ice Mining Experiment-1 (PRIME-1) Payload Operations Summary from the IM-2 Mission,” *The Planetary Science Journal* 7, no.7 (2026): 159, <https://doi.org/10.3847/PSJ/ae732f>.

67. Matthew Hancock et al., “The Polar Resources Ice Mining Experiment-1 (PRIME-1) Payload Operations Summary from the IM-2 Mission,” *The Planetary Science Journal* 7, no. 7 (July 2026): <https://iopscience.iop.org/article/10.3847/PSJ/ae732f>.

68. National Aeronautics and Space Administration (NASA), “NASA Selects Blue Origin to Deliver VIPER Rover to Moon’s South Pole,” September 19, 2025, <https://www.nasa.gov/news-release/nasa-selects-blue-origin-to-deliver-viper-rover-to-moons-south-pole/>.

69. NASA Technical Reports Server (NTRS), *Design of an excavation robot: Regolith Advanced Surface Systems Operations Robot (RASSOR) 2.0*, <https://ntrs.nasa.gov/citations/20210011366>.

70. Elyna Niles-Carnes, “NASA Kennedy Breathes Life into Moon Soil Testing,”

NASA, May 5, 2025, <https://www.nasa.gov/centers-and-facilities/kennedy/nasa-kennedy-breathes-life-into-moon-soil-testing/>.

71. National Aeronautics and Space Administration, "Extraction and Utilization of Water and Gases from Icy Lunar Regolith," NASA TechPort, last updated January 22, 2026, <https://techport.nasa.gov/projects/154566>.

72. Gerald B. Sanders and William E. Larson, "Integration of In-Situ Resource Utilization into Lunar/Mars Exploration through Field Analogs," conference paper, 38th COSPAR Scientific Assembly, Bremen, Germany, July 18–25, 2010, NASA Technical Reports Server, document ID 20100021362, <https://ntrs.nasa.gov/citations/20100021362>.

73. Jennifer E. Edmunson, "Moon to Mars Planetary Autonomous Construction Technology (MMPACT) Lunar Surface Construction Activity at NASA Marshall Space Flight Center," presentation, 2020, NASA Technical Reports Server, document ID 20205007535, <https://ntrs.nasa.gov/citations/20205007535>.

74. Japan Aerospace Exploration Agency, "Asteroid Explorer 'Hayabusa2,'" <https://global.jaxa.jp/projects/sas/hayabusa2/>.

75. The Hague International Space Resources Governance Working Group, Building Blocks for the Development of an International Framework on Space Resource Activities (2019), <https://www.universiteitleiden.nl/binaries/content/assets/rechts-geleerdheid/instituut-voor-publiekrecht/lucht-en-ruimterecht/space-resources/revised-building-blocks-following-the-meeting-of-april-2019.pdf>.

76. United Nations Office for Outer Space Affairs (UNOOSA), "Agreement Governing the Activities of States on the Moon and Other Celestial Bodies," <https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/moon-agreement.html>.

77. National Aeronautics and Space Administration (NASA), "Artemis Accords," <https://www.nasa.gov/artemis-accords/>.

78. China National Space Administration (CNSA), "International Lunar Research Station

(ILRS) Guide for Partnership," June 16, 2021, <https://www.cnsa.gov.cn/english/n6465652/n6465653/c6812150/content.html>.

79. Grand View Research, *Space Mining Market Size and Trends Analysis Report by Asteroid, by Phase, and by Region, and Segment Forecasts, 2025-2030* (2025), <https://www.grandviewresearch.com/industry-analysis/space-mining-market-report>.

80. Raksha Sharma, In-Situ Resource Utilization (ISRU) Market: Global Industry Analysis, Growth, Share, Size, Trends, and Forecast, 2025-2034, report no. AD-600961 (DataIntel, updated April 2026), <https://dataintel.com/report/in-situ-resource-utilization-isru-market>.

81. S. N. Jha, Space Mining Market Size, Market Forecast and Outlook, 2026-2036 (Fact.MR, March 28, 2026), <https://www.factmr.com/report/space-mining-market>.

82. National Aeronautics and Space Administration, "Commercial Lunar Payload Services (CLPS)," NASA Science, last updated January 22, 2025, <https://science.nasa.gov/lunar-science/programs/clps/>.

83. National Aeronautics and Space Administration (NASA), "Moon to Mars Architecture," last updated September 1, 2026, <https://www.nasa.gov/moontomarsarchitecture/>.

84. Xinhua, "International Lunar Research Station Attracts More Partners: CNSA," China National Space Administration, April 24, 2025, <https://www.cnsa.gov.cn/english/n6465652/n6465653/c10670178/content.html>.

85. Indian Space Research Organisation (ISRO), "ISRO and JAXA Gear Up for Joint Chandrayaan-5 / LUPEX Mission in the Technical Interface Meet," May 15, 2025, https://www.isro.gov.in/ISRO_JAXA_CH5_Technical_Interface_Meet.html.

86. Japan Aerospace Exploration Agency, "Lunar Polar Exploration (LUPEX)," <https://humans-in-space.jaxa.jp/en/biz-lab/tech/lupeX/>.

87. ispace, "ispace," <https://www.ispace-inc.com/>.

88. Space Research Institute of the Rus-

sian Academy of Sciences, “Russian Moon Exploration Program,” <http://www.iki.rssi.ru/eng/moon.htm>.

89. Open Lunar Foundation, *ISRU: Lessons Learnt from Mining Governance in Africa* (September 2021), <https://www.openlunar.org/publications/isru-lessons-learned-from-mining-governance-in-africa>.

90. Starlink, Starlink Progress Report 2025 (SpaceX, 2025), https://starlink.com/public-files/starlinkProgressReport_2025.pdf.

91. European Space Agency, “Overview,” European Data Relay System, https://www.esa.int/Applications/Connectivity_and_Secure_Communications/EDRS/Overview.

92. Starlink, “Technology,” <https://starlink.com/technology>.

93. Theresa Hitchens, “SDA Demos Laser Links Crucial for Future SATCOM, Missile Tracking Network,” *Breaking Defense*, September 4, 2024, republished by the Space Development Agency, <https://www.sda.mil/sda-demos-laser-links-crucial-for-future-satcom-missile-tracking-network/>.

94. National Aeronautics and Space Administration, “Laser Communications Relay Demonstration (LCRD),” 2021, <https://www.nasa.gov/mission/laser-communications-relay/>.

95. 3rd Generation Partnership Project, “Non-terrestrial networks (NTN),” May 14, 2024, <https://www.3gpp.org/technologies/ntn-overview>.

96. Apple, “Use Emergency SOS via Satellite on Your iPhone,” Apple Support, https://support.apple.com/en-sa/guide/iphone/iph_968440de/ios.

97. GSMA, *The Limits of D2D*, February 27, 2026, https://www.gsma.com/connectivity-for-good/spectrum/gsma_resources/the-limits-of-d2d/.

98. International Telecommunication Union, *Standardization Consideration of Satellite-Based QKDN*, Technical Report ITU-T TR.SQKDN, March 13, 2025, <https://www.itu.int/epublications/publication/itu-t-tr-sqkdn-2025-03-standardization-consideration-of-satellite-based-qkdn>.

99. International Telecommunication Union, Quantum Key Distribution Network Interworking–Protocol Framework, Recommendation ITU-T Q.4165, January 13, 2026, <https://www.itu.int/epublications/en/publication/itu-t-q-4165-2026-01-quantum-key-distribution-network-interworking-protocol-framework>.

100. European Space Agency, “Eagle-1,” https://www.esa.int/Applications/Connectivity_and_Secure_Communications/Eagle-1.

101. Airbus, “Airbus to Provide Satellite Communications for Armed Forces of Czech Republic and the Netherlands,” September 8, 2022, <https://www.airbus.com/en/newsroom/press-releases/2022-09-airbus-to-provide-satellite-communications-for-armed-forces-of>.

102. Kymeta, “Kymeta Unveils a Paradigm Shift with Kūka Multi-Band Terminal,” <https://www.kymetacorp.com/about/news-insights/kymeta-unveils-a-paradigm-shift-with-kuka-multi-band-terminal>.

103. Starlink, “Starlink Performance (Gen 1) Kit—Specifications,” <https://starlink.com/gb/support/article/1d74cf1d-9db2-552-0-e336-.24ea6b2462cc?srsId=AfmBOooRXtRmSNeLJzG5uxlDIm69wax1FCtZJn8BhD9nVyZ8Hlb2o0B9>.

104. Kymeta, “Kymeta Ships First Flat Panel Antennas for OneWeb’s LEO Network, Marking Major Milestone in Partnership,” March 13, 2023, <https://www.kymetacorp.com/about/news-insights/kymeta-ships-first-flat-panel-antennas-for-onewebs-leo-network-marking-major-milestone-in-partnership>.

105. BAE Systems, “Satellite Communications (SATCOM) Antennas,” April 22, 2025, <https://www.baesystems.com/en-us/product/satcom-antennas>.

106. Intelsat, Set your global SD-WAN Experience Apart, <https://pages.intelsat.com/rs/409-OAJ-662/images/TS-FlexEnterprise-Set-Your-Global-SD-WAN-Experience-Apart.pdf>.

107. SES, “GEO,” <https://www.ses.com/network-and-technology/geo>.

108. SES, “SES Space & Defense to Provide Hybrid Space-Based Architecture to U.S. Department of Defense,” May 13, 2025, <https://www.ses.com/press-release/ses-space-defense-provide-hybrid-space-based-architecture-us-department-defense>.

109. Richard Nunno, Migration to 3G Technology Standards: Europe, Japan, South Korea, and the U.S. (Washington, DC: Federal Communications Commission, 2003), <https://www.fcc.gov/documents>.

110. Richard Nunno, Migration to 3G Technology Standards.

111. Grand View Research, Satellite Communication Market: Size, Share and Trends Analysis Report, 2026-2033 (June 2026), <https://www.grandviewresearch.com/industry-analysis/satellite-communication-market>.

112. MarketsandMarkets, Communication Small Satellite Market by System, Orbit, Mass, Customer, Frequency and Region—Global Forecast to 2030 (August 2026), <https://www.marketsandmarkets.com/Market-Reports/communication-small-satellite-market-176217511.html>.

113. MarketsandMarkets, Optical Satellite Communication Market by Laser Type, Data Rate, Platform, Application, Component, and Region—Global Forecast to 2030 (January 2026), <https://www.marketsandmarkets.com/Market-Reports/optical-satellite-communication-market-181507372.html>.

114. Mordor Intelligence, Optical Satellite Communication Market Size and Share, August 22, 2025, <https://www.mordorintelligence.com/industry-reports/optical-satellite-communication-market>.

115. Fortune Business Insights, Space-Based Data Center Market Size, Share and Industry Analysis, and Regional Forecast, 2026-2034, July 6, 2026, <https://www.fortunebusinessinsights.com/space-based-data-center-market-115870>.

116. Geely, “Geely Constellation Sixth Launch Completes Phase I Deployment With 64 Satellites in Orbit,” September 25, 2025, <https://www.geely.com/en/news/2025/geely-constellation-sixth-launch-deployment-64-satellites-in-orbit>.

[satellites-orbit](#).

117. International Astronautical Federation, “GalaxySpace,” accessed September 17, 2026, <https://www.iafastro.org/membership/all-members/galaxyspace.html>.

118. Orbital Radar, “Qianfan (Thousand Sails),” last reviewed September 7, 2026, <https://orbitalradar.com/glossary/qianfan>.

119. Prime Minister’s Office, “Prime Minister Congratulates ISRO on the Successful Launch of India’s Heaviest Communication Satellite CMS-03,” Press Information Bureau, Government of India, November 2, 2025, <https://www.pib.gov.in/PressReleaseDetail.aspx?PRID=2185583&lang=1®=3>.

120. Dhruva Space, “Dhruva Space,” <https://www.dhruvaspace.com>.

121. Astrogate Labs, “Astrogate Labs,” <https://astrogatelabs.com>.

122. SKY Perfect JSAT Corporation, “SKY Perfect JSAT,” <https://en.skyperfectjsat.space>.

123. Space Compass Corporation, “Space Compass Selected for JAXA’s ‘Space Strategy Fund’—A Significant Step Toward Realizing Next Generation Optical Data Relay Services,” April 22, 2026, <https://space-compass.com/en/news/000090.html>.

124. WARPSPACE, “Solutions,” <https://warpspace.jp/solutions-en>.

125. Bureau 1440, “Bureau 1440,” <https://1440.space/en/>.

126. JSC Satellite System “Gonets,” “Gonets,” <https://gonets.ru/eng/>.

127. Nigerian Communications Satellite (NIGCOMSAT) Limited, <https://nigcomsat.gov.ng/about-us>.

128. Nilesat, “Nilesat,” <https://www.nilesat.com.eg/>.

129. Q-KON, “SKY’S THE LIMIT: Q-KON and Partners Launch Fully Compliant EUTELSAT-ONEWEB LEO Satellite Services in Namibia,” July 22, 2026, <https://www.qkon.com/2026/07/22/q-kon-and-partners-launch-fully-compliant-eutelsat-oneweb-leo-satellite-services-in-namibia>.

[partners-launch-fully-compliant-eutelsat-oneweb/](#).

130. Liquid Intelligent Technologies, “Liquid Intelligent Technologies and Eutelsat Group Bring LEO Satellite Services to Africa,” May 21, 2024, <https://liquid.tech/about-us/news/liquid-intelligent-technologies-and-eutelsat-group-bring-leo-satellite-services-to-africa/>.

131. Vodacom Group, “Vodacom Connects Customers by Land, Sea and Sky to Boost Digital Inclusion in Africa,” November 15, 2023, <https://www.vodacom.com/news-article.php?articleID=13609>.

132. Ayodeji Adegboyega, “Airtel Africa Eyes Starlink Deal to Power Next-Gen Connectivity across 14 African Markets,” Business Insider Africa, February 19, 2026, <https://africa.businessinsider.com/local/markets/airtel-africa-eyes-starlink-deal-to-power-next-gen-connectivity-across-14-african/5yn14en>.

133. Arabsat, “Satellite Ecosystems,” <https://www.arabsat.com/satellite-ecosystems/>.

134. Space42, “Secure Connectivity,” <https://space42.ai/en/lp/secure-connectivity.html>.

135. Es'hailSat, “Es'hailSat,” <https://www.eshailsat.qa>.

136. Neo Space Group, “Neo Space Group: Accelerating Geospatial Impact,” August 25, 2025, <https://neospacegroup.com/english/news/neo-space-group-accelerating-geospatial-impact>.

137. Jean-Jacques Laffont and Jean Tirole, *A Theory of Incentives in Procurement and Regulation* (Cambridge, MA: MIT Press, 1993), <https://mitpress.mit.edu/9780262121743/a-theory-of-incentives-in-procurement-and-regulation/>.

138. European Commission, Directorate-General for Defence Industry and Space, “IRIS²: Secure Connectivity,” https://defence-industry-space.ec.europa.eu/eu-space/iris2-secure-connectivity_en.

139. European Union Agency for the Space Programme (EUSPA), “Galileo,” last

modified June 17, 2026, <https://www.euspa.europa.eu/eu-space-programme/galileo>.

140. National Aeronautics and Space Administration (NASA), Source Selection Statement: Appendix H: Human Landing System, Option A, April 16, 2021, <https://www.nasa.gov/wp-content/uploads/2019/04/option-a-source-selection-statement-final.pdf?emrc=4e09fe>.

141. National Aeronautics and Space Administration, Office of Inspector General, NASA’s Commercial Lunar Payload Services Initiative, Report No. IG-24-013 (Washington, DC: NASA Office of Inspector General, 2024), <https://oig.nasa.gov/wp-content/uploads/2024/06/final-report-ig-24-013-nasas-commercial-lunar-payload-services-initiative.pdf>.

142. European Space Agency, “Industrial Policy and Geographical Distribution,” https://www.esa.int/About_Us/Business_with_ESA/How_to_do/Industrial_policy_and_geographical_distribution.

143. Japan Aerospace Exploration Agency, Research and Development Directorate, “Commercial Removal of Debris Demonstration (CRD2),” <https://www.ken-kai.jaxa.jp/eng/crd2/>.

144. Federal Communications Commission (FCC), Space Innovation; Mitigation of Orbital Debris in the New Space Age, Second Report and Order, FCC 22-74, IB Docket Nos. 22-271 and 18-313, September 30, 2022, para. 18, https://docs.fcc.gov/public/attachments/FCC-22-74A1_Rcd.pdf.

145. Department for Science, Innovation and Technology, Ministry of Defence, *Space Industrial Plan: From Ambition to Action—Advancing UK Space Industry* (London: UK Government, 2024), <https://www.gov.uk/government/publications/space-industrial-plan/space-industrial-plan-from-ambition-to-action-advancing-uk-space-industry>.

146. Howard E. McCurdy, *Financing the New Space Industry: Breaking Free of Gravity and Government Support* (Cham: Palgrave Macmillan, 2019), <https://doi.org/10.1007/978-3-030-32292-2>.

147. McCurdy, *Financing the New Space Industry*.

148. ICEYE, "ICEYE Raises Over-subscribed Growth Funding Round to Expand Global SAR Leadership," April 17, 2024, <https://www.iceye.com/newsroom/press-releases/iceye-raises-oversubscribed-growth-funding-round-to-expand-global-sar-leadership>.

149. European Investment Bank (EIB), "Spain: EIB Finances with €30 Million Sate-
liot's Satellite Network Rollout to Provide IoT Connectivity in Low Coverage Areas," December 4, 2024, <https://www.eib.org/en/press/all/2024-486-eib-finances-with-eur30-million-sateliot-s-satellite-network-rollout-to-provide-iot-connectivity-in-low-coverage-areas>.

150. Intuitive Machines, "Intuitive Machines Advancing Satellite Communications and In-Space Data Processing Capabilities with \$175 Million Strategic Investment," February 25, 2026, <https://investors.intuativemachines.com/news-releases/news-release-details/intuitive-machines-advancing-satellite-communications-and-space>.

151. Reuters, "SpaceX's Business and Finances: Rockets, Satellite Communications and Budding AI," <https://www.reuters.com/business/aerospace-defense/spacexs-business-finances-rockets-satellite-communications-budding-ai-2026-04-01/>.

152. ICEYE, "ICEYE Closes \$65M Extension to Existing Growth Funding Round for a Total of \$158M Raised in 2024," December 18, 2024, <https://www.iceye.com/newsroom/press-releases/iceye-closes-65m-extension-to-existing-growth-funding-round-for-a-total-of-158m-raised-in-2024>.

153. ICEYE, "ICEYE Closes \$65M Extension to Existing Growth Funding Round for a Total of \$158M Raised in 2024."

154. European Investment Bank (EIB), "Spain: EIB Finances with €30 Million Sate-
liot's Satellite Network Rollout to Provide IoT Connectivity in Low Coverage Areas."

155. ICEYE, "Tokio Marine and ICEYE Announce Strategic Investment and

Commercial Collaboration," February 8, 2022, <https://www.iceye.com/newsroom/press-releases/tokio-marine-and-iceye-announce-strategic-investment-and-commercial-collaboration>.

156. Astra, "Astra Announces Closing of Take-Private Transaction," July 18, 2024, <https://astra.com/news/closing-private>.

157. Strategy& and UK Space Agency, *Expanding Frontiers: The Down-to-Earth Guide To Investing in Space* (May 2023), <https://www.strategyand.pwc.com/uk/en/reports/expanding-frontiers-down-to-earth-guide-to-investing-in-space.pdf>.

158. Lockheed Martin, "Lockheed Martin Advances Space Capabilities through Strategic Terran Orbital Acquisition," October 30, 2024, <https://news.lockheed-martin.com/2024-10-30-Lockheed-Martin-Advances-Space-Capabilities-through-Strategic-Terran-Orbital-Acquisition>.

159. Lockheed Martin, "Lockheed Martin Advances Space Capabilities through Strategic Terran Orbital Acquisition."

160. Eutelsat, "Eutelsat Procures a Further OneWeb 229 LEO Satellites from Airbus," September 10, 2026, <https://www.eutelsat.com/media-press/media-centre/news/eutelsat-procures-a-further-oneweb-229-leo-satellites-airbus>.

161. Synspective Inc., "Synspective and Airbus Defence and Space Announce Strategic Partnership to Expand SAR Satellite Data Access," February 10, 2026, <https://www.synspective.com/news/airbus-partnership/>.

162. Lockheed Martin, "Lockheed Martin to Acquire Terran Orbital," August 15, 2024, <https://news.lockheedmartin.com/2024-08-15-Lockheed-Martin-to-Acquire-Terran-Orbital>.

163. SES, "SES Completes Acquisition of Intelsat, Creating Global Multi-Orbit Connectivity Powerhouse," July 17, 2025, <https://www.ses.com/press-release/ses-completes-acquisition-intelsat-creating-global-multi-orbit-connectivity>.

164. SES, "SES Launches SES Open Orbits™ Inflight Connectivity Network," May

29, 2024, <https://www.ses.com/press-release/ses-launches-ses-open-orbitstm-in-flight-connectivity-network>.

165. Airbus Defence and Space, “Airbus Defence and Space and Green-erwave Strengthen Their Strategic Partnership in Satellite Communications through Two New Contracts,” February 25, 2026, <https://space-solutions.airbus.com/resources/news/various/airbus-defence-and-space-and-green-erwave-strengthen-their-strategic-partnership-in-satellite-communications-through-two-new-contracts/>.

166. McKinsey and Company, Technology Trends Outlook 2025 (July 2025), <https://www.mckinsey.com/~media/mckinsey/business%20functions/mckinsey%20digital/our%20insights/the%20top%20trends%20in%20tech%202025/mckinsey-technology-trends-outlook-2025.pdf>.

167. U.S. Department of State, *A Strategic Framework for Space Diplomacy* (Washington, DC: U.S. Department of State, 2023), <https://www.state.gov/wp-content/uploads/2023/05/Space-Framework-Clean-2-May-2023-Final-Updated-Accessible-5.25.2023.pdf>.

168. OECD, *OECD Science, Technology and Innovation Outlook 2025: Driving Change in a Shifting Landscape* (Paris: OECD Publishing, 2025), <https://doi.org/10.1787/5fe57b90-en>.

169. Fortastra, “Strength among the Stars: Fortastra Emerges to Build Maneuverable Spacecraft for National Security,” news release, December 11, 2025, <https://www.fortastra.com/newsroom/fortastra-debut>.

170. HawkEye 360, Inc., Prospectus, filed pursuant to Rule 424(b)(4), Registration No. 333-294965, May 6, 2026, U.S. Securities and Exchange Commission, <https://www.sec.gov/Archives/edgar/data/1750704/000162828026032207/hawkeye360424b4.htm>.

171. Hadrian, “Hadrian Raises \$1.37B Series D to Build Highly Automated Factories to Accelerate America’s Industrial Renewal,” August 6, 2026, <https://www.prnewswire.com/news-releases/>

[hadrian-raises-1-37b-series-d-to-build-highly-automated-factories-to-accelerate-americas-industrial-renewal-302844408.html](https://www.prnewswire.com/news-releases/hadrian-raises-1-37b-series-d-to-build-highly-automated-factories-to-accelerate-americas-industrial-renewal-302844408.html).

172. Julie Bort, “Defense Tech Hadrian Raises \$1.37B at \$8B Valuation,” TechCrunch, August 6, 2026, <https://techcrunch.com/2026/08/06/defense-tech-hadrian-raises-1-37b-at-8b-valuation/>.

173. Marina Temkin, “Jeff Bezos’s Prometheus Raises \$12B to Build an ‘Artificial General Engineer’ for the Physical World,” TechCrunch, June 11, 2026, <https://techcrunch.com/2026/06/11/jeff-bezoss-prometheus-raises-12b-to-build-an-artificial-general-engineer-for-the-physical-world/>.

174. Jagmeet Singh, “India’s Digantara Raises \$50M for Space-Based Missile Defense Tech,” TechCrunch, December 16, 2025, <https://techcrunch.com/2025/12/16/indias-digantara-raises-50m-for-space-based-missile-defence-tech/>.

175. KPMG LLP, COSMOS, Vol. 1.1: 2025 Q4, 2026, <https://kpmg.com/kpmg-us/content/dam/kpmg/pdf/2026/kpmg-cosmos-2025-q4-final.pdf>.

176. Catalyx Space, “Catalyx Space Secures \$5.4 Million Seed Round to Build for the Next Era of Orbital Logistics,” October 30, 2025, <https://www.catalyx.space/funding>.

177. Reuters, “Infinite Orbits Secures 40 Million Euros of New Financing,” November 17, 2025, https://www.tradingview.com/news/reuters.com,2025:newsml_P6N3UQ023:0-infinite-orbits-secures-40-million-euros-of-new-financing/.

178. Dominic-Madori Davis, “Almost 40 New Unicorns Have Been Minted So Far This Year — Here They Are,” TechCrunch, July 5, 2026, <https://techcrunch.com/2026/07/05/almost-40-new-unicorns-have-been-minted-so-far-this-year-here-they-are/>.

179. Varda Space Industries, “Varda Announces \$187 Million in Series C Funding to Make Medicines in Space,” July 10, 2025, <https://www.prnewswire.com/news-releases/var-da-announces-187-million-in-series-c-funding-to-make-medicines-in-space-302502096.html>.

180. Varda Space Industries, “Varda

Announces \$90 Million Series B Funding to Build Factories in Space,” April 5, 2024, <https://www.prnewswire.com/news-releases/varda-announces-90-million-series-b-funding-to-build-factories-in-space-302108949.html>.

181. Stoke Space, “Stoke Space Raises \$1 Billion to Accelerate Fully Reusable Launch,” September 8, 2026, <https://www.stokespace.com/news/stoke-space-series-e>.

182. Stoke Space Technologies, “Stoke Space Technologies Extends Previously Announced Series D Financing to \$860 Million,” February 10, 2026, <https://www.stokespace.com/news/stoke-space-technologies-extends-previously-announced-series-d-financing-to-860-million>.

183. Zang Xiaosong, “Space Pioneer Completes Nearly RMB 2.5 Billion in Pre-D and Series D Financing,” Securities Times, October 9, 2025, <https://stcn.com/article/detail/3371569.html>.

184. Reuters, “China’s Space Pioneer Raises \$207 Mln to Fund Development of Reusable Rockets,” June 6, 2024, <https://www.reuters.com/business/chinas-space-pioneer-raises-207-mln-fund-rocket-development-2024-06-06/>.

185. Antares, “Antares Raises \$470M Series C to Deploy Nuclear Microreactors for Critical Missions,” July 27, 2026, <https://antaresindustries.com/updates/antares-raises-series-c>.

186. Jordan Bramble, “A Letter from Our CEO – Antares \$96M Series B,” Antares, December 2, 2025, <https://antaresindustries.com/updates/a-letter-from-our-ceo-antares-96m-series-b>.

187. PM Insights, “Relativity Space Valuation Analysis: Latest Market Insights & Trends,” accessed September 15, 2026, <https://www.pminsights.com/companies/relativity-space>.

188.

Melissa de Zwart, Stacey Henderson, and Michelle Neumann, “Space Resource Activities and the Evolution of International Space Law,” *Acta Astronautica* 211 (October 2023): 155–162, <https://doi.org/10.1016/j.actaas->

[tro.2023.06.009](https://doi.org/10.1016/j.actaas-tro.2023.06.009).

189. Tim Fernholz, “Starcloud Raises \$250 Million for Orbital Data Centers as Launch Options Dry Up,” TechCrunch, August 21, 2026, <https://techcrunch.com/2026/08/21/starcloud-raises-200-million-for-orbital-data-centers-as-launch-options-dry-up/>.

190. Tim Fernholz, “Starcloud Raises \$170 Million Series A to Build Data Centers in Space,” TechCrunch, March 30, 2026, <https://techcrunch.com/2026/03/30/starcloud-raises-170-million-series-a-to-build-data-centers-in-space/>.

191. Simran Pant, “Transcelestial Expanded Funding Will Power Japan’s Critical, National Defence and Space Communications with Laser Technology,” Transcelestial, November 11, 2025, <https://transcelestial.com/blog/transcelestial-expanded-funding-will-power-japans-critical-national-defence-and-space-communications-with-laser-technology/>.

192. Simran Pant, “Transcelestial Brings Laser Communications Investment to Australia and Japan’s Telecom, Defence and Space Infrastructure,” Transcelestial, June 30, 2025, <https://transcelestial.com/blog/transcelestial-brings-laser-communications-investment-to-australia-and-japans-telecom-defence-and-space-infrastructure/>.

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