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Implications of Emerging Technology for UK Space Regulation Policy

Findings of a Horizon Scan

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Preface

This report summarises the findings of a short, one-month RAND study into the intersection of key emerging technologies with the space domain, both now and out to 2040. It considers the implications of projected future technology trends for the development of novel space capabilities and applications, both in upstream and downstream markets – while acknowledging that the pace, direction and wider externalities of such developments will also be shaped by non-technological factors, not least regulation.

It is impossible to predict the future and this study does not seek to prescribe what the future will or should look like. Rather, it aims to illustrate the sorts of trade-offs and dilemmas that technology may pose for future space regulation policy, as the UK seeks to strike a balance between mitigating risk (e.g., to space safety, security or sustainability, or to terrestrial activities dependent on space data and services) and, at the same time, maximising opportunity (e.g., to deliver broad societal and economic benefits and support delivery of other policy goals, through promotion of a vibrant and competitive space sector).

This quick-turnaround study was commissioned in November 2023 by the Department for Science, Innovation and Technology (DSIT) and the Regulatory Horizons Council (RHC), in support of the RHC's independent advice and contribution to a wider UK Government review of space regulation policy. It was contracted through the Government Office for Science (GO Science)'s Future Framework, and delivered by RAND Europe, the European arm of the RAND Corporation, the world's largest non-profit policy research organisation. RAND's aim is to help improve public policy and decision making through objective research and analysis. The study brought together researchers from RAND Europe's Centre for Futures and Foresight Studies (CFFS) and the RAND Space Enterprise Initiative (RSEI), a global hub for RAND's space-related research, analysis and gaming. It also built on previous and ongoing horizon scanning work for the UK Space Agency, the Defence Science and Technology Laboratory, and others across government.

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Summary

This report presents the findings of a one-month study exploring emerging technologies and space capabilities by RAND Europe and commissioned by the Regulatory Horizons Council (RHC). It aims to explore the intersection between seven critical technology areas and the space sector, with the goal of identifying space capability trends and their implications for future space regulation. The research draws on a literature scan, bibliometric analysis, horizon scanning, and a stakeholder workshop hosted by the RHC, and aims to provide practical insights for enhancing future space regulatory policy.

The Intersection of Emerging Technology with Space Capability

The technologies and capabilities presented in this report have the potential to transform uses of space, both incrementally through offering improvements on existing technologies, and more radically, by enabling entirely new capabilities, use cases and markets. Illustrative examples of such impacts include:

- **AI, autonomy and robotics** can improve data analytics and decision making, as well as contributing to active debris removal and in-orbit servicing, while enabling the exploration of celestial bodies such as the Moon and Mars using a mix of uncrewed spacecraft and human-machine teaming.
- **Telecommunication technologies** have the potential to drastically improve connectivity and data transmission, with the potential for space-based data centres to enhance security and efficiency, while increasing the efficiency of data processing.
- **Quantum technologies** offer advances in communication, computing and sensing technologies, with the potential to enhance – or undermine – data security and the encryption of satellite communications. Similarly, the implementation of quantum metrology could bring significant improvements to spacecraft navigation and communication, while terrestrial use of quantum technologies could boost resilience by providing alternatives to space-based services (e.g., alternatives to reliance on GPS, Galileo, etc.).
- **Engineering biology** holds promise towards the development of food and medicine, which could help sustain life in space, while improving the provision of health services, both on Earth and for space missions, through scientific breakthroughs such as advanced tissue engineering.
- **Semiconductors** can help improve the hardware capabilities, performance and longevity of satellites, data transmission and the accuracy of manoeuvres and measurements, with the potential to enhance space-based services such as positioning, navigation, and timing (PNT), satellite communications (SATCOM) and remote sensing to improve lives on Earth.

- **Energy and propulsion** advancements have the potential to enable faster and more efficient space travel, unlocking future uses of space for exploration, tourism, crewed missions and the transport of minerals and materials back to Earth, as well as providing new sources of energy for activities in space (e.g., space-based nuclear) or on Earth (e.g., space-based solar power to terrestrial use).
- **Novel materials and advanced manufacturing** can improve the value-for-money, scale, number, diversity and performance of space-based assets. This could unlock a wide range of ambitious new possibilities, including space-based powerplants, habitats, factories, repairs and refuelling.

Opportunities and Risks for the United Kingdom (UK)

- Emerging technology is helping drive new space capabilities and use cases with the potential to drive economic growth, enhance national security and advance scientific research, with spillover effects felt across almost all industries and parts of society. However, barriers such as a shortage of suitably qualified and experienced personnel (SQEP) in the UK could limit realisation of benefits.
- The UK is well-placed to act as an international broker for space diplomacy and has the potential to gain the first mover's advantage by proactively shaping the global space regulatory environment.
- Increasing militarisation of space, proliferation of debris, and potential for attacks on space-based assets all pose significant threats to UK's space capabilities. Other nations are investing heavily in their own national space sectors, driving fierce competition – including on regulation.

Implications for Space Regulation Policy

- This study identifies a range of both technology-specific and cross-cutting implications for UK space regulation, both in the near-term and out to 2040. Resolving any regulatory gaps and areas of friction or confusion would help encourage investment into the UK space sector, and pursuit of novel missions and revenue streams. At the same time, industry's desire to move quickly will need to be balanced against safety and environmental concerns, amongst other dilemmas.
- Research highlights the need for a continuous pursuit of both incremental and radical innovations, backed by a more adaptive and anticipatory approach to UK space regulation policy in future. The UK is in a good position to leverage innovative mechanisms such as regulatory sandboxes, as well as employing strategic foresight methods and new tools such as AI to assist with more agile development of regulation fit for a fast-changing sector.
- 'Hard' regulation is only one of a wider set of levers that the UK Government can use to help shape the future of space governance, both at home and globally, so as to gain a competitive advantage while avoiding a regulatory race to the bottom.
- If the UK is to deliver on its ambition to be a genuine thought leader on space regulation, this implies a need for regulators to have access to funding, talent, technology and organisational processes and culture that enable continuous learning, adaption and the absorption of innovation – both in terms of the novel space capabilities to be regulated, and of the cutting-edge regulatory approaches that the UK uses to shape the evolution of this fast-moving sector in its favour.

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Abbreviations

AGI	Artificial General Intelligence
AI	Artificial Intelligence
ADR	Active Debris Removal
AEPS	Advanced Electric Propulsion System
ASAT	Anti-Satellite
BEIS	Department for Business, Energy and Industrial Strategy
BWX	Babcock & Wilcox
CAA	Civil Aviation Authority
CEA	Commissariat à l'énergie atomique et aux énergies alternatives
CFFS	Centre for Futures and Foresight Studies
COPUOS	United Nations Committee on the Peaceful Uses of Outer Space
CSpO	Combined Space Operations Initiative
DARPA	Defense Advanced Research Projects Agency
DfT	Department for Transport
DNA	Deoxyribonucleic Acid
DRACO	Demonstration Rocket for Agile Cislunar Operations
DSIT	Department for Science, Innovation and Technology
Dstl	Defence Science and Technology Laboratory
EM	Electromagnetic
EO	Earth Observation
EPS	Electric Propulsion System
ESA	European Space Agency
ESO	European Southern Observatory
EU	European Union
FCDO	Foreign, Commonwealth and Development Office
FOCA	Swiss Federal Office of Civil Aviation
GO Science	Government Office for Science

GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GVA	Gross Value Added
ICAO	International Civil Aviation Organisation
ISR	Intelligence, Surveillance and Reconnaissance
ISRU	In-Situ Resource Utilisation
ISS	International Space Station
ITU	International Telecommunication Union
JAXA	Japan Aerospace Exploration Agency
JWST	James Webb Space Telescope
KET	Key Enabling Technology
LEO	Low-Earth Orbit
LLM	Large Language Model
ML	Machine Learning
MOD	Ministry of Defence
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NTR	Nuclear Thermal Rocket
OECD	Organisation for Economic Co-operation and Development
OEWG	United Nations Open-Ended Working Group
Ofcom	Office of Communications
OST	Outer Space Treaty 1967
PAROS	Prevention of an Arms Race in Outer Space
PLA	Polylactic acid
PNT	Positioning, Navigation, and Timing
QKD	Quantum Key Distribution
R&D	Research and Development
RAF	Royal Air Force
RHC	Regulatory Horizons Council
RSEI	RAND Space Enterprise Initiative
S&T	Science and Technology
SABRE	Synergetic Air-Breathing Rocket Engine
SATCOM	Satellite Communication
SDA	Space Domain Awareness

SEP	Solar Electric Propulsion
SORA	Specific Operations Risk Assessment
SQEP	Suitably qualified and experienced personnel
SSA	Space Situational Awareness
SST	Space Surveillance and Tracking
STM	Space Traffic Management
TRL	Technology Readiness Level
UK	United Kingdom
UKSA	United Kingdom Space Agency
UN	United Nations
UNN	Unnatural Amino Acid
US	United States

1. Introduction

This chapter introduces the context and objectives for this short study, and outlines its approach and methodology, the associated caveats and limitations, and the structure of this report on RAND's findings.

1.1. Background

1.1.1. Innovation in technology and commercial models has enabled a new race for space, which is becoming increasingly congested, contested and competitive.

Governments, economies and societies are increasingly dependent on space for positioning, navigation, timing (PNT), satellite communications (SATCOM), Earth observation (EO) and meteorological services.[1] The size of the global space sector is also growing, with its value projected to grow to US$558bn (£419bn) by 2026, up from US$360bn (£270bn) in 2018.[2] Space science and exploration are also seeing renewed excitement and investment. The James Webb Space Telescope (JWST) is providing scientists with new insight into the Universe.[3] The United States (US) National Aeronautics and Space Administration (NASA) aims to return astronauts to the Moon by 2025 through its Artemis programme, as a precursor to interplanetary missions to Mars in the coming decade.[4] This follows the successful deployment of lunar rovers by India and China, and a flurry of uncrewed missions to the Moon's surface or orbit by countries as diverse as South Korea, Luxembourg, Israel, Japan and the United Arab Emirates – not to mention competing initiatives to establish permanent lunar settlements for scientific, military or commercial purposes.[5]

Aiming at reinforcing the calibre of terrestrial and in-orbit services, the last decade has seen an impressive increase in the number of objects launched into space, with a staggering 2,478 objects launched in 2023 compared to just 120 in 2010.[6] This growth is largely due to the emergence of major private actors (e.g., SpaceX, Blue Origin, etc.) and the so-called NewSpace economy.[7] Increased competition and innovation have driven down launch costs per kilogram of mass, while also promoting miniaturisation and extracted

[1] Black (2018).

[2] Research and Markets (2018).

[3] JWST (2023).

[4] NASA (2020b).

[5] Osburg & Lee (2022); Dobos (2022); Palkowsky (2023).

[6] Mathieu, et al. (2022).

[7] ESA (2019b).

better performance out of satellites and their onboard components. These trends, in turn, are making it both technically and financially feasible to unlock new use cases and applications from space technology: establishing mega-constellations in low-Earth orbit (LEO) to enable global connectivity; bringing Earth observation (EO) capabilities that used to be the sole domain of state intelligence agencies onto the general market; and launching a race to put billionaires, tourists and even a Tesla into space.[8]

At the same time, governments, militaries, and NGOs have all raised concern about the increasingly 'congested, contested, and competitive' nature of the space domain.[9] Russian and Chinese tests of direct-ascent anti-satellite (ASAT) missiles have generated considerable debris clouds in recent years, causing damaging collisions with satellites and even threatening the crew of the International Space Station (ISS); there have also been a series of high-profile cyber and electronic attacks (e.g., dazzling, jamming, spoofing) against space systems and ground infrastructure, and an uptick in various other ambiguous or threatening behaviours, such as unwanted close-proximity manoeuvres around high-value or military satellites.[10] Besides purposefully hostile activity, there is also the risk of accidental collisions, electromagnetic (EM) spectrum fratricide, or damaging environmental impacts as Earth orbit and cis-lunar space become more cluttered.[11]

In this context, ensuring space safety, security and sustainability necessitates both international and domestic efforts to balance risk and opportunity from increasing space-based activity. Globally, this entails diplomatic initiatives to de-escalate interstate tensions and promote responsible behaviour, whether through normative or legal mechanisms (e.g., building on the Outer Space Treaty [OST] of 1967, the Liability Convention of 1972, Registration Convention of 1974, or Moon Agreement of 1979).[12] At home, this means making sure national legislation (i.e., the UK Outer Space Act of 1986), regulations, licensing regimes, standards and other forms of rule or guidance all remain fit for purpose in a fast-changing sector.

1.1.2. The United Kingdom (UK) aspires to be a "meaningful player" in space, leveraging its unique strengths, with new technology and regulation both key enablers if done right.

Getting the regulatory balance right and adapting for the future are priorities for a review into UK space regulation policy by the Department for Science, Innovation and Technology (DSIT), due to conclude in March 2024. This ongoing effort supports the policy ambitions of the National Space Strategy, published in 2021, which aims to increase the UK's share of the global space market and to contribute to wider prosperity through investing in space capabilities, supporting space innovation, encouraging international collaboration, and promoting commercial opportunities in the space sector.[13] The security dimension is

[8] Black, et al. (2022).

[9] Ligor & McClintock (2022).

[10] Secure World Foundation (2023).

[11] McClintock, Feistel, et al. (2021); McClintock, et al. (2023); Ligor & Matthews (2022); Ligor, et al. (2023).

[12] Ligor (2022); Irving (2023).

[13] BEIS, et al. (2021); UK Space Agency, et al. (2021).

further addressed through an accompanying Defence Space Strategy, issued in 2022, recognising the dual-use or dual-purpose nature of so many space-related technologies, capabilities and areas of infrastructure.[14]

Amid a fierce international competition, the UK boasts a plethora of strengths in the space sector, including:

- Strong alliances and partnerships, particularly within the United States, North Atlantic Treaty Organisation (NATO), Five Eyes, AUKUS and the European Space Agency (ESA).
- Establishment of a National Space Council and increased cross-governmental collaboration (especially between DSIT and the Ministry of Defence [MOD], or the UK Space Agency [UKSA] and new UK Space Command), along with deepening engagement with industry and academia.
- Ambitious plans to be the first space launch site in continental Europe, with efforts underway to establish a series of space ports for vertical and horizontal launch.
- Access to UK Overseas Territories and favourable geography at a range of latitudes and longitudes, of relevance both for responsive launch and for Space Surveillance and Tracking (SST) missions.[15]
- Strong domestic cross-sectoral links and niche space capabilities, such as SABRE and small sats deployed through the New Space growth strategy.[16]
- Scientific advances via the current space science projects portfolio and a thriving academic sector.

At the same time, the UK remains a small player in terms of its domestic market and financial clout, as compared to the United States, China, India, or other major European nations, and thus must make efficient use of all potential levers to secure a competitive advantage. This drives a need to review the space regulatory framework and its alignment with departmental objectives and international agreements (e.g. the Artemis Accords or the Space Operations Vision 2031, which sets out the objectives of the UK and partner nations within the Combined Space Operations Initiative [CspO]).[17] Effective regulation is crucial for positioning the UK as a competitive nation to attract investment into both the upstream and downstream segments of the space economy, particularly for companies interested in licensing, launching and operating space objects from the UK, while mitigating the risk of unintended harms or spillovers from space-related activities.[18]

In addition to this wider DSIT-led review of space regulation policy, the Regulatory Horizons Council – a committee of independent experts that advises the government on the impact of technological advancements and the necessary regulatory changes to facilitate their swift and secure implementation – is

[14] Slapakova, et al. (2021) ; MOD (2022b) ; Retter, et al. (2022).

[15] For example, the UK hosts a tracking radar for the US-led Space Surveillance Network at RAF Fylingdales in Yorkshire and an optical telescope on Diego Garcia in the Indian Ocean. The UKSA and Space Command are also investing in a new telescope on Cyprus, where the UK maintains two Sovereign Base Areas, and the UK will collaborate with the US and Australia to establish a new deep space radar in Pembrokeshire as part of trilateral cooperation on the Deep Space Advanced Radar Capability (DARC) through AUKUS. See: RAF (2023); MOD (2023).

[16] BEIS, MOD & UKSA (2021).

[17] NASA (2020a); MOD (2022a).

[18] In this regard, national space regulation compliments wider UK Government efforts to shape the future uses of space in a beneficial direction reflecting the OST and other legal instruments, as well as UK-led efforts to promote responsible behaviours in space and the formulation of norms through, inter alia, a UN Open Ended Working Group.

conducting its own independent review of the regulatory impact of future space technologies.[19] The aim is to investigate how the five critical technologies identified in the UK Government's Science and Technology (S&T) Framework[20] (i.e., artificial intelligence (AI), engineering biology, future telecommunications, semiconductors and quantum technologies) could be applied to the space sector and how regulatory reforms can help safely unlock these applications, whilst ensuring they deliver full value to society. Overall, the Regulatory Horizons Council (RHC)'s goal is to ensure that future space regulation policy is positioned to enable the safe, swift and effective utilisation of new technologies to maximise their benefits for humanity, the planet and the UK.

1.2. Research objectives

This research seeks to inform RHC reporting, with the aim to leverage RAND Europe's expertise and track record, particularly through its Centre for Futures and Foresight Studies. This report feeds into the wider work of the RHC, providing an evidence base for the identification of future space capabilities ahead of the RHC analysis of the UK regulatory landscape. The objectives of this short, one-month study are to:

- **Identify key intersection points:** Identify and analyse the areas within the space sector where the five critical technologies can be integrated for potential benefits.
- **Assess regulatory gaps:** Support the RHC's ongoing wider analysis of existing space regulations to pinpoint regulatory gaps and challenges in accommodating these emerging technologies.
- **Develop adoption strategies:** Inform development of strategies and recommendations for ensuring effective utilisation of these technologies within the space sector.
- **Maximise benefits for the UK:** Inform exploration of ways to maximise the economic and societal benefits of integrating these technologies into the space sector while considering national interests.
- **Integration with existing initiatives:** Ensure that the study complements the wider ongoing Space Regulation Review by focusing on topics (e.g., technology) that are outside the review's core focus.
- **Inform policy development:** Provide practical implications and insights for enhancing regulatory governance, from the perspective of the above technology horizon scanning exercise, which will be integrated into the final Space Regulation Review expected to be published in March 2024.

Based on the above, the team derived a set of research questions (RQs) to guide the study:

1. How might the emerging technology areas identified in the UK Government's S&T Framework (a) intersect with capability development for the space domain, and (b) shape the sector's evolution out to 2040 in terms of both opportunities and risks?
2. What is the potential impact of these developments on how the UK regulates the implementation of new technologies for space, and where are there regulatory gaps or dilemmas to be addressed?

[19] Regulatory Horizons Council (2023).

[20] DSIT & Prime Minister's Office (2023).

3. What might the UK do to address these regulatory gaps or dilemmas, and overcome these obstacles to fully leverage the space sector and contribute to wider UK prosperity?

As such, the study aims to focus in on the intersection of emerging technologies with the space domain, understanding how these may translate into new capabilities and use cases, and thus behaviours that the UK might wish to shape through regulation (e.g., whether to encourage, enable, ban or de-risk). It is not intended as a broader review of other non-technological factors that will shape the future space sector, nor does it duplicate the wider analysis of UK space regulation policy being undertaken by the RHC and DSIT.

1.3. Study approach and methodology

This study employed a mixed-method approach, including: i) a scoping review, in which the current state of UK space regulation was identified for wider team awareness, ii) data collection, whereby bibliometric analysis and horizon scanning helped identify relevant emerging technologies, iii) a workshop with RHC, DSIT and other regulator, industry or academic experts to discuss the possible impact of emerging space tech and capabilities, and iii) a targeted literature review into the critical technologies and the related implications for space regulations and the UK. These methods are explained in more detail in Annex A.

1.4. Caveats and limitations

- This project was delivered within a short timeline and with limited resources and, as such, the data collection and analysis activities were necessarily constrained.
- At the RHC's direction, the focus was on the five technologies identified as critical in the UK Government's S&T Framework. While RAND added other priority areas based on horizon scanning to broaden the scope somewhat (namely, energy and propulsion technologies, and advanced materials), it is not possible for this short study to go into depth on all relevant areas of S&T. As such, the findings are intended as an illustrative cross-section of relevant advances and their potential implications for space regulation policy, not an exhaustive list of technology trends.
- Similarly, the potential use cases and applications of the technologies mentioned in this study were not analysed in-depth, though the study sought to focus on capabilities instead of specific technologies where possible. Further research into the non-technological factors affecting the barriers or enablers to, and likely timelines for, commercialisation and adoption would be needed to understand the potential benefits and risks to the UK – and thus the full regulatory implications.
- More generally, the future is inherently uncertain. This study does not aim to predict or prescribe what the future of the space domain will or should be, but rather to illustrate potential future directions for technological and capability development, based on current trends. The ongoing Space Regulation Review provides an opportunity to shape this future in the UK's favour.

1.5. Report structure

- **Chapter 2** discusses how technologies translate into capability and use cases to be regulated.
- **Chapter 3** summarises the intersections of selected technology areas with space capability **(RQ1a)**.
- **Chapter 4** discusses the opportunities and risks for the UK **(RQ1b)**.
- **Chapter 5** examines the implications in terms of gaps and dilemmas for space regulation **(RQ2).**
- **Chapter 6** concludes by examining ways of future-proofing space regulation policy **(RQ3).**
- **Chapter 7** provides final reflections from the research team.

This report also contains a bibliography and three annexes with the methodology and tech write-ups.

2. Emerging technology in context

This brief chapter sets out the basic conceptual framework and assumptions for the rest of the report. More specifically, it examines the wider context in which critical technologies are used in the space domain, including their role in space value chains, and as building blocks of space capabilities. This serves to bridge between the defined scope of this tech-focused study for the RHC, and the primary focus of UK regulation policy, which looks not to regulate technologies but rather capabilities, use cases and markets.

2.1. Core assumptions

2.1.1. Technology is only one factor for space regulation policy to consider

As the spacefaring community develops novel technologies, there is the potential to unlock a range of different futures through new space activities and applications. From improving AI to leap forward advances in satellite technology which could enable new capabilities for Earth observation, weather forecasting, and telecommunications, humans are also embarking on missions to explore our solar system and establish space-based habitats. The technology areas discussed in Chapter 3 reveal a multitude of ways in which space capabilities can unleash potential benefits – and problematic risks, dependencies or externalities.

Nevertheless, before discussing the critical technology areas in turn, it is important to position their development in a wider context, elaborating on their implications for the space domain and how they contribute to future space capabilities. The research, development, fielding and exploitation of such technologies occurs against the backdrop of myriad political, economic, social, legal, environmental and military (PESTLE-M) trends shaping the space domain. As such, technology should be understood as just one element of future space capability – with the space ecosystem a complex socio-technical system also comprising elements such as funding, talent, skills, networks and regulation. While the possible direction of these wider PESTLE-M trends, and how they may generate different potential future worlds out to 2040, are not covered in this short tech-focused study, they will be addressed in wider work by RHC and DSIT.

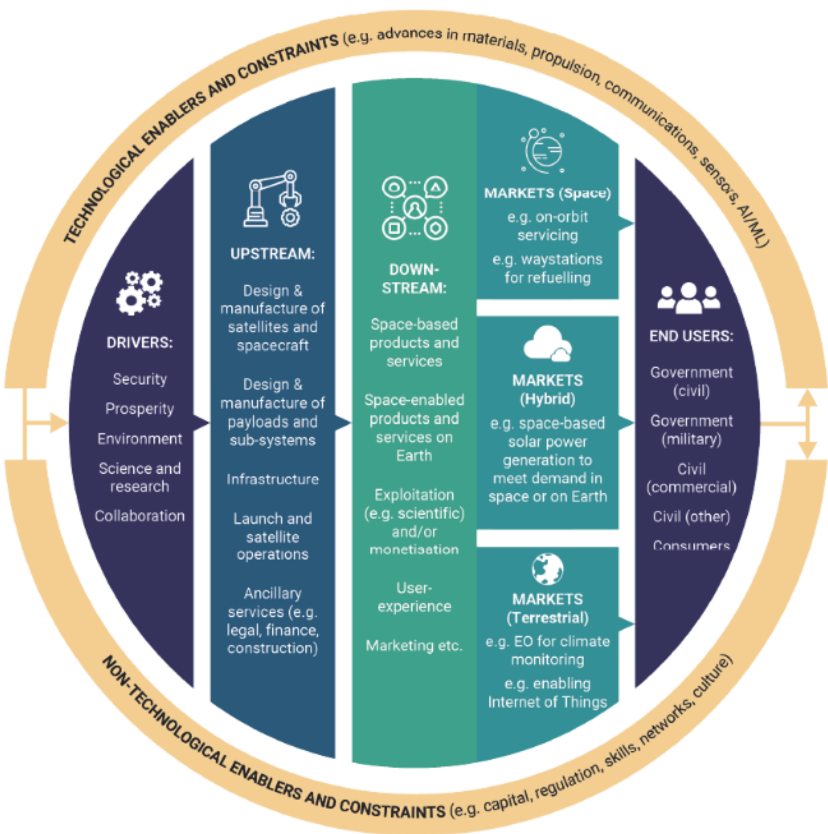
2.1.2. Technology offers building blocks for future space capabilities and use cases

Emerging technologies such as those identified in the UK Government's S&T Framework have important implications for the space domain, as they are potential building blocks towards future space capabilities that enable a wide range of applications. Critical and emerging technologies can both enhance existing space capabilities and contribute to the creation of entirely new ones. Enhancements to existing capabilities can include, for instance, improvements to SATCOM systems, upgrades to the efficiency of spacecraft propulsion, and the integration of new instruments or software into existing satellites. Examples of more novel capabilities in space technologies could include ground-breaking new propulsion systems, the use of advanced materials and in-situ resource utilisation (ISRU) to construct new types of structure in outer space, or the invention of technical means for sustaining lunar or interplanetary settlements. Both types of capability developments are important for advancing space exploration and technology, and both can lead to advancements in scientific research, economic growth and national security.

2.1.3. The impact of technological innovation is felt across both the upstream and downstream segments of the space economy, driving diverse new markets

The technology areas covered in this study can all be exploited for terrestrial, hybrid as well as space-based markets, due to the wide scope of their potential application. Furthermore, they also feed into both the upstream and downstream segments of the global space economy by, for instance, facilitating the design and manufacturing of spacecrafts or supporting space missions. This 'upstream' and 'downstream' categorisation of the space economy is often used by space agencies and organisations worldwide to make sense of the value chain in the space domain. The upstream segment involves 'activities related to sending spacecraft and satellites into space, including the manufacturing of launch vehicles and satellites', while the downstream involves 'activities utilising space data to offer products or services (space applications) as well as ground segment applications (space operations)'.[21]

Figure 2.1 Contribution of technology to shaping the upstream and downstream space economy



Source: Slapakova, et al. (2022).

[21] OECD (2019).

The UK continues to contribute to and benefit from both the upstream and downstream segments of the space economy. The upstream space economy creates jobs in areas such as manufacture and, soon, launch, while contributing to economic growth and wider prosperity. The downstream space economy has potential to boost innovation and improve services depending on SATCOM, EO and PNT, which could generate growth across a range of industries, including transport and logistics. In the UK, the downstream is measured to be the largest source of space sector income, at 71 per cent.[2] Downstream applications of space capabilities have various societal benefits too, such as environmental and public health monitoring. Hence, regulation can play a crucial role in shaping how benefits and costs/risks are either socialised or privatised, with the potential to even generate public revenues (including through ownership stakes and warrants, or the 'polluter pays' principle, in addition to the positive spillovers of space to the economy and tax base).[3]

This report consequently uses the 'upstream' and 'downstream' categorisation to better understand how critical technologies discussed in Chapter 3 feed into the development of space capabilities and thus activities and markets to be regulated.

2.1.4. Regulation is one of many factors shaping how technology develops

While advancements in critical technologies and the commercialisation of space are likely to improve the adoption of new space capabilities, significant barriers remain in terms of funding, governance, regulatory frameworks, incentives, and risk appetites related to capability uptake. While it is beyond the scope of this short study to examine these in depth, some cross-cutting enablers that will positively impact the uptake and integration of critical technologies into future space capabilities are[4]:

- Investment in key enabling technologies – and better utilisation of existing technology.
- Pathways to access finance and support commercialisation (incl. public-private partnerships).
- The falling cost of launch, increasing access to orbit and making new products/services viable.
- Fostering public discourse as well as public and political interest in space.

At the same time, various barriers exist that could slow or hinder the adoption and/or application of new technologies in space capabilities, including but not limited to[5]:

- Limited access to funding and structural inefficiencies in public and private sector mechanisms.
- Barriers to sector-wide innovation and adaptation within industry and its supply chains.
- Uncertainties concerning Technology Readiness Levels (TRLs), appetites for risk, as well as future ethical and governance frameworks for future space applications.
- Insufficient and fickle – or, conversely, excessively ponderous and onerous – national and international legal and regulatory mechanisms.
- Challenges in the development of effective space domain awareness, debris removal and associated risk-mitigations to avoid a breakdown in safe and secure access to space.

While the UK is in a good position to shape the future regulatory environment for the space domain, including the use of critical technologies, then, it is essential to consider these technologies in their wider context to fully understand their complex interactions with wider trends in the space economy and regulatory environment – posing new challenges for regulators, but also potential opportunities.

3. Intersection of emerging technology with space capability

This chapter builds on the previous discussion of how emerging technologies form the building blocks of novel space-related capabilities and uses cases, by summarising the possible intersections of each of the critical technologies identified in the Government's S&T Framework with the space domain. This list of five key technologies provided by the RHC is augmented by two additional areas suggested by RAND.

The sections below outline a brief description of each technology area, and examples of how this might translate into space capabilities and use cases. Each short summary is supported by a longer discussion of the technology area in question in Annex B, which explores:

- Near-term technology trends (based on bibliometric analysis and a literature scan)
- Possible developments out to 2040 (based on horizon scanning)
- How these could translate into new space capability and use cases
- How these could prompt new considerations for space regulation in the UK.

This technology-focused analysis across Chapter 3 and Annex B, in turn, feeds in subsequent chapters, which will look at the cross-cutting issues that arise from the combination of multiple technologies, along with non-technological factors (e.g., finance, labour), to create new space-related applications and markets that must be proactively shaped through, inter alia, effective regulation to maximise the benefits and mitigate the risks for the UK. This will include regulatory gaps and dilemmas, and consideration of how to address both the international and domestic dimension of space regulation and adapt the UK's regulatory approach and toolkit to keep pace with rapid technological change.

3.1. Summary: intersections with the space domain

As the space sector continues to incorporate new technologies, there is the potential to unlock a range of different futures through new space activities and applications. From improving AI to advances in satellite hardware which could enable new capabilities for Earth observation, weather forecasting and telecommunications, or the colonisation of cis-lunar space, or lunar surface and Mars, a mix of state and private actors are investing heavily in technological innovation to enable a growing range of missions.

Examples of major intersections between individual technology areas with the space domain include:

- **AI, autonomy and robotics** can improve data analytics and decision making, as well as contributing to active debris removal and in-orbit servicing, while enabling the exploration of celestial bodies such as the Moon and Mars using a mix of uncrewed spacecraft and human-machine teaming.
- **Telecommunication technologies** have the potential to drastically improve connectivity and data transmission, with the potential for space-based data centres to enhance security and efficiency, while increasing the efficiency of data processing.
- **Quantum technologies** offer advances in communication, computing and sensing technologies, with the potential to enhance – or undermine – data security and the encryption of satellite communications. Similarly, the implementation of quantum metrology could bring significant improvements to spacecraft navigation and communication, while terrestrial use of quantum technologies could boost resilience by providing alternatives to space-based services (e.g., alternatives to reliance on Global navigation satellite system [GNSS] such as the Global Positioning System [GPS], Galileo).
- **Engineering biology** holds promise towards the development of food and medicine, which could help sustain life in space, while improving the provision of health services on Earth and for space missions, through scientific breakthroughs such as advanced tissue engineering.
- **Semiconductors** can help improve the hardware capabilities, performance and longevity of satellites, data transmission and the accuracy of manoeuvres and measurements, with the potential to enhance space-based services such as PNT, SATCOM and remote sensing to improve lives on Earth.
- **Energy and propulsion** advancements have the potential to enable faster and more efficient space travel, unlocking future uses of space for exploration, tourism, crewed missions and the transport of minerals and materials back to Earth, as well as providing new sources of energy for activities in space or on Earth.
- **Novel materials and advanced manufacturing** can improve space travel and the performance of space-based assets through light-weight, high-strength components. The adoption of self-healing materials, for example, has the potential to increase the lifespan of satellites and reduce the need for in-orbit maintenance.

Notably, the intersections between each of these technology areas and the space domain are not all equally mature. Some areas of R&D and technological innovation have long been established with operations in the space domain. Robotic systems have long been used in space, for example, given the vast majority of space objects are uncrewed, as have various communications technologies and other electronic systems derived from semiconductors. By contrast, there has much less history of engineering biology in a space setting. Across all areas, however, space is only one of many sectors where such technologies can be applied, meaning it is not the primary driver of innovation (unlike, say, in the 1960s, when the sheer scale, ambition and resources of the Apollo mission acted to channel the direction of R&D across multiple areas of S&T and to 'crowd in' private-sector investment in areas of interest to NASA).[22]

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[22] Mazzucato (2021).

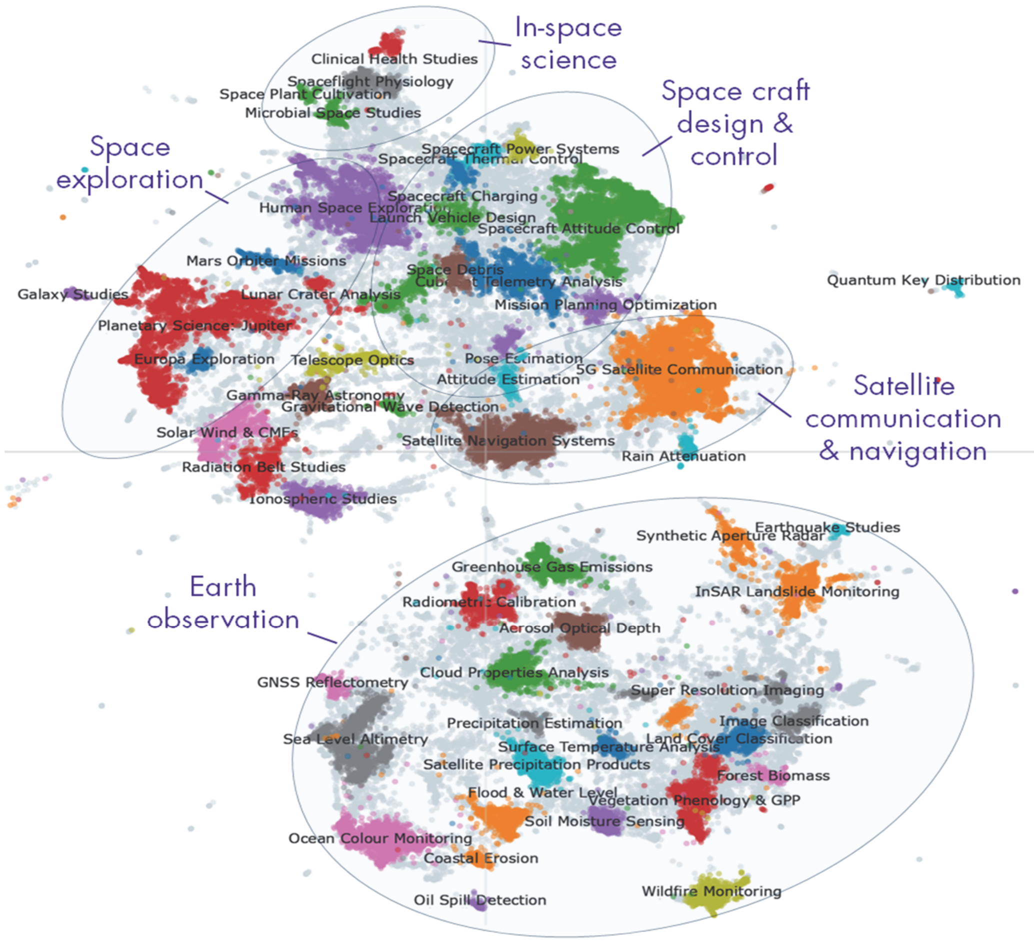
To illustrate this, the table below compares the intersections with space in published scientific research.

Table 3.1 Comparison of intersections between space and technology areas in publications data

Technology area	Search area (space +...) in OpenAlex	Count
All of space sector	Space flight, exploration & in-orbit economy	122,100
AI	Artificial intelligence and machine learning	26,700
Future telecommunications	Telecommunications	22,900
Quantum	Quantum mechanics and electrodynamics	21,800
Semiconductor	Electrical, electronic and computer engineering	8,600
Engineering biology	Synthetic biology, biotech, bioinformatics, biomedical engineering	350
Energy and propulsion	Propulsion, solar energy, nuclear energy	2,517
Novel materials and manufacturing	Additive manufacturing, materials, material science	3,700

Source: RAND Europe analysis of OpenAlex scientific publications data from 2017 onward (2023).

Figure 3.1 Focus areas for scientific research publications in space, as of 2023



Source: RAND Europe analysis (2023). Note: This covers scientific publications through OpenAlex for the period 2017-2023. Each abstract is represented by a small marker and colour-coded by cluster. LLM-generated labels are shown for prominent clusters. See Annex A for more detail.

3.2. Critical technology 1: AI, autonomy, and robotics

AI refers to machines that can perform various functions independently, simulating human intelligence. AI is a critical technology as it can help address complex problems that are difficult or impossible for humans to solve on their own. It can also help automate repetitive tasks, improve situational awareness and decision-making, especially under tight timeframes, and provide insights into large amounts of data.[23]

Related fields of S&T investment and activity include machine learning (ML), autonomy, human-machine teaming (HMT), and robotic systems of varying levels of sophistication, automation, and capacity for collaboration (e.g., multiple systems cooperating in a swarm, or a mothership-and-drone configuration).

Table 3.2 Examples of capabilities and use cases for AI, autonomy and robotics

Segment	Illustrative examples out to 2040
Upstream	• Insights from AI will help to unlock new design and maintenance approaches for space assets, increasing their performance, efficiency, safety, and resilience, boosting value-for-money across the capability lifecycle. • AI will increasingly help to assist with spacecraft design, manufacture, and operations (e.g., autonomous navigation and docking), as well as continuous modelling of digital twins for both terrestrial and space-based systems, helping to predict faults, optimise sensor and network performance, conserve energy, etc. • Advances in autonomy and robotics promise to provide space systems with new hardware capabilities (e.g., enabling Active Debris Removal [ADR], refuelling and in-orbit servicing in the medium-term, or the establishment of resource-extraction and manufacturing complexes in the longer-term). • Autonomous and robotic systems are already used widely in exploration (e.g., probes, rovers); further advances could enable orbital, cis-lunar, Moon or Mars settlements.
Downstream	• The use of AI and ML to make sense of space data could benefit a range of downstream industries and activities, including EO for agriculture, transportation, logistics, finance, telecommunications, and other purposes (e.g., environment, land use, or climate and weather monitoring and modelling). This, in turn, can lead to the creation of valuable new markets (e.g., AI-enabled, space-based climate monitoring could support development of new financial products associated with carbon net zero and the green transition). • The use of AI and ML, along with edge computing, can also help to reduce the amount of data that needs to be transmitted between satellites and ground stations, e.g., by automatically deleting cloudy or otherwise not usable satellite imagery, thereby optimising energy, storage, and bandwidth usage, and reducing costs.[24] • The ability to collect and analyse data from space-based sensors will be crucial not only for myriad civilian purposes, but for national security users as well, enabling monitoring of potential threats, decision support tools for military command and control, and satellite connectivity for uncrewed systems.

Source: RAND Europe analysis (2023).

Further information is provided in Section B.1, including tech-specific considerations for space regulation.

[23] Menthe, et al. (2021).

[24] ESA (2023).

3.3. Critical technology 2: telecommunication technologies

Telecommunication is the transmission of information by various types of technologies over wire, radio, optical or other electromagnetic systems. It has evolved significantly over the years, from traditional landline phone calls to the internet, mobile networks, and is now increasingly dependent on space-based assets and capabilities. Future telecommunications include a range of technologies such as space-based global broadband communication and web services, space laser communication technology, flexible satellites, quantum-encrypted communications, electromagnetic spectrum management, in-space communications relay, satellite backhaul, and space-based data centres. These technologies enable the transmission of information between multiple locations through electrical signals or electromagnetic waves.

Table 3.3 Examples of capabilities and use cases for future telecommunications technologies

Segment	Illustrative examples out to 2040
Upstream	• The integration of AI/ML into telecommunications will aid network optimisation, predictive maintenance, and energy efficiency, as examples.[25] These advances will both drive costs down and improve technical capabilities including reduced latency. • Space-based assets will become integrated into an Internet of Things (IoT) in space.[26] This interconnectivity will enhance navigation and communication, improving the monitoring and collection of data about spacecraft, the Earth, and beyond. • Flexible satellites that can be reprogrammed once in space offer the opportunity to respond to changing demands over time.[27] • With the growth of data-intensive technologies like AI and the Internet of Things (IoT), there's increasing demand for data storage and processing. As a greater share of this data is either generated in or transferred through space, there will be greater demand for space-based data centres, leveraging abundant solar power and natural cooling.[28]
Downstream	• The advent of LEO satellite mega-constellations, such as those launched by SpaceX's Starlink project, promises to provide high-speed, low-latency internet access globally.[29] By 2040, we could see a fully-fledged 'internet from space' globally. • As the internet from space expands, so too will the IoT By 2040, we could see a fully connected world, with billions of devices communicating with each other, transforming manufacturing, agriculture, healthcare, and transportation industries among others. IoT's growth will require robust and extensive network coverage, that space-based infrastructure has the potential to provide. • 6G+ communications will help realise new business models and even more advanced downstream technologies.[30] This could include immersive technologies such as VR, AR and MR that will likely require high-speed, low-latency networks to function effectively.

Source: RAND Europe analysis (2023).

Further information is provided in Section B.2, including tech-specific considerations for space regulation.

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[25] ESA (2023).

[26] Kua, et al. (2021).

[27] UK Space Agency (2021).

[28] Thales Alenia Space (2022).

[29] Marquina (2022).

[30] Nguyen, et al. (2022).

3.4. Critical technology 3: quantum technologies

Quantum technologies refer to technologies resulting from the quantum effects of quantum mechanics.[31] Quantum technologies include quantum computing,[32] quantum sensing, quantum simulation, quantum measurement and quantum materials. Quantum technologies are essential as they have the potential to revolutionise computing, communication, navigation, encryption, and sensing. In the space sector, these technological developments could be applied to improve communications and operational efficiency.

Table 3.4 Examples of capabilities and use cases for future quantum technologies

Segment	Illustrative examples out to 2040
Upstream	• Quantum communication could enable new space-based communications channels to be secured through physical properties, rather than simple encryption that can be hacked.[33] Quantum cryptography can enhance security against adversaries using quantum communication technology, and Quantum Key Distribution (QKD) could enable secure inter-satellite and long-distance satellite-to-ground optical communications. • Quantum technologies have the potential to improve the accuracy of spacecraft navigation and communication, as well as the detection and characterisation of gravitational waves. • Quantum technologies could support future efforts towards space debris removal, by enabling the rapid and efficient selection of debris, as well as optimised routes and fuel requirements.[34]
Downstream	• Developments in quantum technologies have the potential to improve EO capabilities, ranging from seismic activity monitoring and analysis; atmospheric gas monitoring; water quality monitoring; wildfire monitoring; landslide detection; and air pollution analysis. • Space-based magnetometry may have military and defence applications, such as submarine detection.[35] Future quantum radiofrequency sensing could lead to improvements in intelligence, surveillance and reconnaissance and electronic warfare.[36] Quantum imaging, which detects targets at range and mainly uses the particle nature of light, can have potential military applications such as for ISR and PNT, especially in GPS-denied environments.[37] • Quantum sensing can contribute to Earth observation and help mitigate the challenges of climate change and environmental events.[38]

Source: RAND Europe analysis (2023).

Further information is provided in Section B.3, including tech-specific considerations for space regulation.

[31] Ibaraki (2022).

[32] Quantum computers use qubits and exploit quantum properties like superposition and entanglement that both significantly accelerate the computer's data processing speed. Superposition means a qubit is a mix of 0 and 1 but collapses into a specific state when observed, whilst entanglement is when particles become correlated, so measuring one determines the state of the other, even at large distances. Source: Gunashekar, et al (2022).

[33] ESA (2023).

[34] Short (2023).

[35] Krelina (2023).

[36] Krelina (2023).

[37] Silberglitt, et al. (2022).

[38] Short (2023).

3.5. Critical technology 4: engineering biology

Engineering biology applies engineering principles to biology, enabling the manufacture of novel biological systems, such as cells or proteins, which can be applied across a wide range of sectors, including food, materials and health.[39] Bioengineering has the potential to revolutionise space exploration by enabling the development of various new applications, from new materials for spacecraft, to supporting life in space.

Table 3.5 Examples of capabilities and use cases for engineering biology

Segment	Illustrative examples out to 2040
Upstream	• Engineering biology could contribute to the development of lightweight and durable materials which could be used in space suits, spacecraft and future habitats. • There is also the potential for engineering biology to enable closed-loop life support systems to sustain astronauts in space through water recovery and the production of oxygen. Increased supportability could minimise logistic resupply requirements from Earth. • Further, engineering biology processes could allow crews to produce food and materials. For example, NASA is developing a technology that can convert carbon dioxide and water into organic compounds to enable microbial biomanufacturing of food products, vitamins, plastics and medicine.[40] • Advances in engineering biology could contribute to the production of biofuels through the treatment of wastewater, which could enable self-sufficient energy production for spacecraft, allowing for longer transit times for crewed missions. • Engineering biology has the potential to ensure the health of astronauts during long voyages, by addressing challenges associated with dental health, tissue engineering and emergency wound closure. Wearable biosensors and the ability to regrow tissue could prove critical in enabling crewed missions to Mars and beyond. • Human augmentation could allow humans to endure a wider range of environments and prevent illness under adverse conditions, potentially enabling longer voyages in space.
Downstream	• Bio-inspired sensors and imaging systems could be used to provide high-resolution and cost-effective images of the space environment and Earth, which could have application for a range of industries reliant on image analysis, such as agriculture, environmental monitoring and national security. • There is also potential for new pharmaceutical drugs to be developed and tested in space, making use of the microgravity environment to experiment medicines under conditions not possible on Earth. The ISS is currently hosting tests of HIV/AIDs drugs, with potential for further such experiments to take place.[41]

Source: RAND Europe analysis (2023).

Further information is provided in Section B.4, including tech-specific considerations for space regulation.

[39] Council for Science and Technology (2023).

[40] NASA (2018).

[41] Varda (2023).

3.6. Critical technology 5: semiconductors

Semiconductors are key components with specific electrical properties, which are vital to modern computing and electronic devices. Semiconductors play a crucial role in the design and manufacture of electronic components for satellites, including microprocessors, memory chips, and power amplifiers. These components are essential for the operation of satellites and other space-related digital technology, including for various applications such as communication, navigation, and remote sensing.

Table 3.6 Examples of capabilities and use cases for semiconductors

Segment	Illustrative examples out to 2040
Upstream	• Advances in semiconductor technologies are likely to have significant impacts on space hardware, allowing for miniaturisation and improved performance, making space assets lighter, cheaper and more powerful. • The ability of spacecraft to communicate over longer distances without deterioration due to radiation and other challenges of the space environment could enable crewed and uncrewed missions to the Moon and Mars. Improved communication through advancements in semiconductor technology also contributes to humanity's ability to sustain space habitats over the longer term. • Smaller and more powerful semiconductors could enable advanced solar photovoltaic cells, improving the solar sails of satellites and allowing them to travel further distances. Advanced semiconductors could allow for the creation of space solar farms to harness the sun's energy above the atmosphere and transmit this power back to Earth. • Semiconductors could contribute to improved sensing technologies, enhancing our understanding of celestial bodies and increasing space situational awareness. Advances in semiconductor technologies could improve the accuracy and range of space probes and rovers, enabling deeper exploration of our solar system and neighbouring planets and asteroids.
Downstream	• Semiconductors have the potential to improve the speed and accuracy of data transmission and analysis, allowing higher volumes of data to be processed between spacecraft or with ground stations. As such, semiconductors may contribute to improved GNSS and PNT, and could have considerable spillover effects across sectors such as transport, logistics, communication and national security. • As an enabler of other critical technologies such as Quantum and AI/ML, advances in semiconductor technology could empower rapid processing of data, with the potential to advance developments in autonomous technologies, robotics and other areas.

Source: RAND Europe analysis (2023).

Further information is provided in Section B.5, including tech-specific considerations for space regulation.

3.7. Critical technology 6: energy and propulsion

Energy and propulsion are essential enabler for space activities. Advancements in these fields could make it possible to create faster, more efficient and more sustainable space travel. It could also enable permanent settlement of celestial bodies and lead to the realisation of new paradigms of the space economy, such as in-orbit manufacturing. Related fields are those that have to do with natural resource exploration and exploitation, mining, critical minerals and advanced materials.

Table 3.7 Examples of capabilities and use cases for energy and propulsion technologies

Segment	Illustrative examples out to 2040
Upstream	• Improved propulsion technologies can make spacecraft more energy efficient. This can enable faster and longer space missions. • Currently, spacecraft are designed primarily in function of their fuel system. For example, rockets need to carry very large fuel storage tanks. Implementing different propulsion systems could reduce the design constraints imposed on spacecraft. • Sustainable energy sources can reduce the environmental impact of space travel. • The in-situ exploitation of energy sources could be a fundamental enabler for the construction of long-term bases.
Downstream	• Data provided by space assets can help improve the efficiency of terrestrial energy systems, for example by aiding the forecasting of wind speeds and solar irradiance.

Source: RAND Europe analysis (2023).

Further information is provided in Section B.6, including tech-specific considerations for space regulation.

3.8. Critical technology 7: novel materials and manufacturing

Novel materials and manufacturing can transform the space sector by enabling the development of lightweight, high-strength spacecraft and satellite components. They can also improve solar panel performance, thermal control systems and radiation shielding, while reducing mission costs through reusable spacecraft and reduced maintenance.

Table 3.8 Examples of capabilities and use cases for novel materials and manufacturing

Segment	Illustrative examples out to 2040
Upstream	• Additive manufacturing is likely to have a significant impact on the space sector, due to the reduced cost and complexity of spacecraft components. • There is currently research underway to test the use of lunar or Mars regolith as a material source for additive manufacturing, with the potential to enable in-space manufacturing, thereby reducing the energy required to move large quantities of materials into space for on-site construction of habitats and launch infrastructure.[42] • Lighter and more resilient materials could further reduce costs and improve the lifespan of objects, enabling reuse of launchers and components, facilitating deep-space missions. • The ability for materials to self-heal could have significant implications for the space capabilities, where assets may not be accessible for in-orbit maintenance or repair. • The use of bio-based materials such as wood is being tested to improve sustainability and leverage the cheap and lightweight properties of the material. For example, LignoSat, a joint NASA and Japan Aerospace Exploration Agency (JAXA) project, seeks to launch the first wooden satellite into orbit in 2024.

Source: RAND Europe analysis (2023).

Further information is provided in Section B.7, including tech-specific considerations for space regulation.

[42] NASA (2015).

4. Opportunities and risks for the UK

This chapter draws from the emerging technologies outlined briefly in Chapter 3 and examined in more detail in Annex C and turns to the related opportunities and challenges for the UK. There are likely to be significant scientific, economic, security and diplomatic benefits across both the upstream and downstream segments of the space economy. However, it is important to weigh these benefits against the various challenges, ranging from resourcing challenges to security risks. This chapter provides a high-level overview of these key issues, building both on literature and the stakeholder workshop convened for this study, which may help regulators as they address challenges associated with emerging space capabilities out to 2040.

4.1. Opportunities for the UK

As space exploration and technology continue to advance, new and emerging space capabilities present opportunities for the United Kingdom. The UK has a long history of space exploration and has made significant contributions to the field. The country has a thriving space industry, leveraging both the upstream and downstream segments of the space economy, with companies involved in satellite manufacture, launch services and space data applications.

As an island nation with a long coastline, the UK is geographically well-placed to host launch services, with development underway for spaceports across the country to reach in-demand orbits. The UK has the potential to capitalise on new and emerging space capabilities to drive economic growth, enhance national security, and advance scientific research. By investing in space technology and infrastructure, fostering innovation, and collaborating with international partners, the UK can position itself as a leader in the global space industry and reap the benefits of this rapidly evolving field.

4.1.1. The UK promotes scientific innovation and has an outsized impact on global S&T research and development of space capabilities.

The UK has a strong tradition of scientific research, making significant contributions to the field, with 40 per cent of all small satellites currently in orbit built in the UK.[43] The UK's contributions to the JWST is already generating significant scientific insights across a number of areas, including cosmology, exoplanet studies, the formation of stars and planets, and study of the solar system. The UK-built Rosalind Franklin Mars Rover is also expected to launch to Mars in 2028, with the potential to enhance our understanding of

[43] ADS (2018).

Mars and its potential for supporting life.[44] There is potential for the UK to have an outsized impact on scientific space discovery, already ranking third in the world for published scientific research.[45]

The UK launch sector is on the rise, with plans for seven sites underway, offering vertical and horizontal launch across the UK. The UK-US Technology Safeguards Agreement enables US companies to operate from UK spaceports and export space launch technology, providing the UK access to US customers and revenues. Spaceport Cornwall is home to the Centre for Space Technologies, which includes the Space Systems Integration Facility, Space Systems Operations Facility, and R&D Facility. Combined, Cornwall's space cluster is breaking ground on developments in launch and spaceflight, while leading on sustainable practices with plans to roll out a Road to Net Zero roadmap to reduce the carbon impact of launch.[46]

The UK has implemented a "cluster" approach to the space industry, bringing together stakeholders from industry, government, and academia, particularly through initiatives such as Harwell Campus (see Box 4.1). This approach has thus far shown to be successful, enabling scientific collaboration, and the sharing of lessons and resources. Clusters play a key role in empowering small and medium enterprises (SMEs), contributing to the interconnected UK space ecosystem.[47] Creating an environment where innovations flourishes and access to emerging technologies is ensured is essential for the UK so it can maintain its competitive edge in the international arena and continue to lead on scientific breakthroughs.

Box 4.1 Overview of the Harwell Space Campus

The Harwell Space Campus in the UK is widely regarded as a good practice example for the development of a thriving space industry ecosystem. The campus is situated on a former RAF site and brings together a range of organisations, including government agencies, research institutions, and private firms, to collaborate and innovate. Notably home to the ESA Business Incubation Centre and the Satellite Applications Catapult, Harwell campus offers laboratories, testing facilities, and business support services, to support the development of new technologies and applications. The campus has successfully attracted investment and fostering innovation and become a hub for UK space industry.

Source: Vorley, et al. (2019).

4.1.2. The UK is well-placed to grow the upstream and downstream space economy.

Given the limited size of its domestic market compared to the major spacefaring nations and economic blocs (e.g., the United States, the EU, China, increasingly India), the UK cannot hope to excel in all areas of the space value chain. Nonetheless, it has considerable strengths that it can bring to bear in key niches, including the ability to draw on areas of comparative advantage in other sectors (e.g., finance, insurance, AI, quantum, life sciences, pharma, creative arts, education, etc.). In turn, advances in space technology and capabilities of the kind discussed in Chapter 3 are likely to impact almost all areas of the UK economy out to 2040 and beyond. This is depicted in Figure 4.1 overleaf, drawn from a 2021 RAND study for the UK Space Agency to inform development and implementation of the National Space Strategy.

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[44] BEIS, MOD & UKSA (2021).

[45] British Council (2023).

[46] Launch UK (2023).

[47] Space Enterprise Community (2022).

Figure 4.1 Examples of sectors impacted by rollout of future space technologies and capabilities

Agriculture
Space-based food production and space-based services for the terrestrial agricultural sector

Climate & environmental protection
Space-based and space-enabled applications for environmental protection and mitigating the effects of climate change, global warming and environmental degradation

Energy
Applications for space-based energy production, storage and utilisation for space and terrestrial needs, as well as space-based applications for terrestrial energy markets (e.g. modelling of market dynamics and monitoring of energy infrastructure)

Construction, repair & engineering
Construction and maintenance of space-based infrastructure as well as use of space-based services for connectivity and monitoring for terrestrial construction

Extractive industries
Asteroid, comet and planetary mining for water, metals and other resources, as well as space-based applications for terrestrial resource extraction (e.g. connectivity for mining Industrial Internet of Things [IIoT])

Tourism, culture & entertainment
Space-based culture and entertainment services, including space tourism, and provision of entertainment and culture in space, as well as space-enabled content and connectivity for arts, culture and entertainment markets

Defence, security and safety
Applications for providing and ensuring security and safety of the space environment (e.g. debris mitigation and planetary defence) and terrestrial populations

Finance and commerce
Applications of space-based services in global finance and trade and financial technological innovations contributing to the development of the space economy (e.g. trust and privacy services)

Health, medicine & pharmaceuticals
Space-based health, telehealth and telemedicine services, space-based medical research and applications for terrestrial pharmaceutical and healthcare services including medical and pandemic response

Illicit activities
Uses of space for illicit or criminal purposes, including space-based criminality (e.g. space piracy, hacktivism and protests), and terrestrial crime (e.g. cyber and electronic attacks on space objects or satellite-enabled criminal activities)

Logistics
Space-based logistics services (e.g. commercial resupply and material recycling), and use of space-based applications, particularly EO and satellite connectivity for terrestrial logistics systems and operations

Manufacturing
Manufacturing in space, including on-orbit or planetary assembly and additive manufacturing, and space-based applications for terrestrial manufacturing (e.g. connectivity and PNT for the Industrial Internet of Things)

Science, research and education
Space exploration (including crewed, uncrewed and robotic missions) and use of space for scientific, research and education purposes on Earth (e.g. connectivity for e-learning and research and academic institutions)

Telecommunications
In-space communications and space-based telecommunications services for space and terrestrial activities (e.g. next-generation SATCOM, fixed and mobile satellite communications and global broadband)

Transport
In-space transportation systems and services (e.g. traffic management and safety-critical services), and space-based applications for air, maritime and land transport (e.g. vehicle-to-vehicle communications, support to driverless vehicles etc.)

Source: Black, et al. (2022).

Given the breadth of industries that stand to see innovation arising from space services, the UK continues to contribute to and benefit from both the upstream and downstream segments of the space economy:

- **Upstream:** the upstream space economy creates jobs in areas such as satellite manufacture and launch applications, while contributing to economic growth and wider prosperity. The upstream sector heavily relies on imports for approximately 60 per cent of its inputs, ranging from small electronic components to large subsystems. However, the sector also has a strong export market, and the balance between imports and exports is roughly equal.[48]
- **Downstream:** the downstream space economy has potential to boost UK innovation and improve existing services through satellite data analytics and improved PNT, which could generate growth across a range of industries, including transport and logistics. In the UK, the downstream sector is measured to be the highest source of space sector income, at 71 per cent.[49] There are numerous downstream applications with public benefits, such as environmental and public health monitoring. Public procurement or regulation can play a crucial role in these applications due to their wider benefits, with the potential to save public funds and even generate funds through the "polluter pays" principle.[50]

Overall, a flourishing space sector could attract investment in the UK, boost the economy, and create high-paying jobs across the UK, in line with the levelling up agenda. UK space industry growth rates between 2019/20 and 2020/21 reached 5.1 per cent, outperforming global growth at 1.6 per cent.[51] In the same timeframe, the space economy contributed an estimated £7 billion Gross Value Added (GVA) to the UK economy, not taking into consideration supply chain effects (which added £18.3 billion total GVA effect).[52]

4.1.3. The UK has a long history of partnerships in space exploration and technology, offering a platform to contribute to global space governance.

A permanent member of the UN Security Council and the Five Eyes alliance, as well as a strong NATO member, the UK has a strong foothold in international space security. The UK is also a member of ESA and has strong ties with the United States and other spacefaring nations. The Artemis Accords, led by the United States and signed by 26 countries including the UK, sets out some of the broader principles to govern behaviours and norms in space. The UK is also a member of multilateral organisations involved in space governance, including the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) and the International Telecommunication Union (ITU). These provide fora for engagement with other countries on governing space activities. The UK has also made outsized contributions to the United Nations Open-Ended Working Group (OEWG) on promoting responsible uses of space. The OEWG was established in 2018 to develop a set of guidelines for the responsible use of space, with the aim

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[48] Space Enterprise Community (2022).

[49] Space Enterprise Community (2022).

[50] Space Enterprise Community (2022).

[51] UK Space Agency (2023).

[52] UK Space Agency (2023).

of promoting the long-term sustainability of space activities, with the UK playing a major role in driving activity.

As such, the UK is well-placed to act as an international broker for space diplomacy. The UK benefits from not having the same geopolitical challenges and baggage as the United States in the eyes of many smaller nations when it comes to space, due to the historically dominant position of the United States in this domain.[53] Strong international partnerships, technical expertise, and a relatively neutral position in global politics can enable the UK to build trust and facilitate cooperation between countries with different interests. The UK has the potential to gain the first mover's advantage by proactively shaping the global space regulatory environment and setting the agenda for regulatory debates. This could help ensure that the regulatory environment is evolving in a way that is beneficial for the UK.

4.2. Risks and challenges for the UK

There are also several risks and challenges for the UK. A shortage of suitably qualified and experienced personnel (SQEP) has the potential to limit UK advancements in the sector. The increasing militarisation of space, the proliferation of space debris, and the potential for cyber-attacks on space-based assets all pose significant threats to the UK's space capabilities. Additionally, the UK faces competition from other countries, particularly China and Russia, who are investing heavily in space technology and exploration.

4.2.1. Developments in the space can be hindered by the lack of highly skilled workers, including data analysts, engineers and software developers.

The shortage of SQEP in the UK was highlighted in the Space Sector Skills Survey 2023, which revealed that more than half of UK organisations report skills gaps in their current space workforce.[54] The survey showed that organisations with skills gaps experience reduced productivity, problems with product and service delivery, struggle to remain competitive and are less likely to introduce new technologies. Skills gaps in the UK are reportedly most noticeable in electronics, systems engineering and spacecraft operations.[55] Though entry-level recruitment may be oversubscribed, the pool of skilled individuals atrophies at the more senior levels, in part due to intense competition for key software and data skills in other sectors with higher pay. This has the potential to limit government's ability to deliver across the areas of space strategy, policy, capability development, and operations, especially considering the central role that complex enabling technologies will play in the future of the space sector. [56]

4.2.2. An increasingly crowded space domain has seen a proliferation of new actors, giving rise to new security challenges both in orbit and on Earth.

Today, most critical national infrastructure is reliant on access to space, and space as a domain plays a unique role as an enabler of defence operations, enabling a range of warfighting capabilities for countries

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[53] Retter, et al. (2022).

[54] Space Skills Alliance (2023).

[55] Space Skills Alliance (2023).

[56] Retter, et al. (2022).

with access to space infrastructure.[57] Overall, space assets often perform dual-use functions with both military and civilian uses. This can mean that satellites may be seen as attractive targets, in order to weaken adversaries or deny key defence capabilities.

Challenges include an increased risk of accidental or intentional escalation of crises, damage caused by space debris, and cyber, electronic, and physical attacks on space-based systems.[58] There is also potential for attacks on satellites to have intentional or unintentional spillover effects, generating debris or causing collisions, which could threaten the safety of other orbits for civil and commercial purposes.[59] The United States, Russia, China and India have invested in ASAT capabilities, with Russia conducting a test of a direct- ASAT missile against a satellite target in 2021.[60] The test generated over 1,500 trackable pieces of debris, risking the integrity of other space assets in LEO, as well as posing a risk to humans onboard the International Space Station.[61]

Along with kinetic or physical attacks, there is an increased risk of non-kinetic attacks on satellites, such as hacking, jamming or spoofing. Broadening supply chains in the space industry and the use of components from a variety of sources, generates the risk for hostile activity in lower tiers of the supply chain, through building in loopholes into systems allowing adversaries to compromise these.[62] While advances in quantum technologies may provide additional security and protection from hacking, the ongoing race to improve quantum-enabled satellites could see China seek to penetrate stealth military technologies, denying the United States and its allies air superiority in the event of conflict.[63] Russia and China's collaboration and exponential growth of space capabilities has intensified the militarisation of space, with efforts underway to enhance Intelligence, Surveillance and Reconnaissance (ISR) capabilities, as well as to grow their arsenals of space-based kinetic and non-kinetic weapons. The exploration of the Lunar surface and Mars could accelerate competition, particularly with regard to resources and the construction of space-based support infrastructure. To avoid excessive competition and militarisation, there is likely to be a need for diplomacy and collaboration to ensure that space remains a domain for peaceful cooperation and exploration.

As technology proliferates, there is also potential for state and non-state actors to bypass legislation and conduct illegal launches and deployment of satellite systems, posing a challenge to regulation and enforcement. For example, US Satellite start-up Swarm Technologies conducted an unauthorised launch of four satellite prototypes in 2018 onboard a commercial Indian launcher, defying the US Federal Communications Commission and receiving a fine of $900,000.[64] Though the assets were swiftly detected, there is potential for further such activity to take place, particularly if nations lower regulatory standards to attract businesses (the space-faring equivalent of flags of convenience in maritime shipping). Recently, the

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[57] Retter, et al. (2022).

[58] Black, et al. (2022).

[59] Retter, et al. (2022).

[60] Panda (2021).

[61] Panda (2021).

[62] Retter, et al. (2022).

[63] Howell (2023).

[64] Sheetz (2018).

North Korean government announced plans to launch a military satellite, which violates UN sanctions which prohibit the nation from testing ballistic missile technology used for space launches.[65] The emergence of rogue launch nations – or state-backed proxies, acting with plausible deniability and seeking to undermine global norms or wage irregular warfare against target states – could give rise to further illicit launches of potentially unsafe or harmful systems which may damage other satellites or the environment.[66]

Another challenge resulting from the new dynamics of the space domain is the lack of resources for the UK, and its allies, to thwart the growing financial, industrial and technological grasp that some competitors are gaining in strategic space-related sub-sectors.[67] Foreign Direct Investment (FDI) encourages economic growth and prosperity, but can also be a geoeconomic tool that allows the investor to secure a desired dependence from the receiver nation, influencing decision-making within the targeted sector.[68] This influence is acutely felt in technology sectors, as it can dictate the direction of innovation and even pose security threats.[69] From 2018 to 2023, for example, Chinese FDI became a trend in the space industry through the significant amounts of money invested in European space startups and American firms, enabling China to indirectly control technological advancements from these enterprises.[70] To circumvent the associated risks, further scrutiny should be exercised when accepting FDI, along with stricter regulation, as is currently the case in the Indian space sector.[71] The UK has similarly included satellite and space technologies among the list of 17 areas of the economy of priority interest to the National Security and Investment Act (NSI Act), and continues to evolve its monitoring and enforcement regime.[72]

Relatedly, the risk of Intellectual Property (IP) theft remains an important issue among space companies and universities, with the United States in particular airing concerns on preventing IP theft of space programmes by Chinese actors.[73] While industrial collaborations, foreign students and academic exchanges all remain key to furthering scientific discovery, there is a need to balance these benefits against security risks in order to safeguard IP and data – and, with this, the UK's strategic advantage in space.[74]

The security of supply chains for key enabling technologies, such as semiconductors, and essential raw materials remains an area of concern. In 2022, RAND conducted a tabletop exercise exploring the geopolitical implications of Taiwan's semiconductor dominance, given the nation's tensions with the People's Republic of China (PRC). The study found that there are considerable risks associated with the concentration of semiconductor production and there is a need to diversify supply chains to mitigate these.[75] Similarly, the export of key components and resources from China poses a risk due to imposed export

[65] Tingley (2023).

[66] Klein (2023).

[67] Chronopoulos (2023).

[68] OECD (2019).

[69] Evroux, et al. (2023); DIT (2021).

[70] Alamalhodaei (2023); Kelly (2018); Zenglein, et al. (2022).

[71] Pandey (2023).

[72] Cabinet Office (2023).

[73] Erwin (2021).

[74] Quimbre, et al. (2022); Dortmans, et al. (2022).

[75] Martin, et al. (2023).

quotas of rare earth elements, for example, intended to artificially restrict the availability of materials to increase prices outside the country and incentivise relocation of foreign business to China.[76] The UK will need to take supply chain security into consideration to remain at the forefront of technology innovation and ensure the safety and security of future space assets.

While the UK is in a good position to leverage its existing scientific, diplomatic and intelligence clout, and strong partnerships (e.g., CSpO), there remains a need to take into consideration the scale and pace at which competition and conflict could escalate, and how best the UK could contribute alongside its allies.[77] Enhancing the UK's ability to deter, de-escalate, be resilient against, and recover from potential conflict in space is essential if the UK is to mitigate security challenges and thereby continue to benefit from the scientific and economic opportunities of being a key spacefaring nation.[78]

[76] Villalobos (2022).

[77] Moroney, et al. (2023).

[78] MOD (2022b).

5. Implications for Space Regulation

This chapter explores the cross-cutting implications for future space regulation policy arising from the various technological intersections and space capability developments discussed in Chapters 2 to 4. It begins with a brief overview of the relevant areas of national and international space law and regulation. It then provides examples of the sorts of possible regulatory gaps and areas for clarification that emerge from ongoing technological innovation in the space domain – differentiating between those pertaining to the near-term rollout of certain new space capabilities, and those longer-term issues which, while not yet felt as acutely, will only become more pressing over time as the space ecosystem evolves out to 2040 and beyond. Finally, the chapter frames some of the trade-offs and dilemmas that regulators face when trying to grapple with these issues thrown up by the intersection of emerging technologies with space capability development.

5.1. Implications of novel technologies and capabilities for regulation

5.1.1. The UK strives to become a thought leader in space regulation, promoting sustainability, innovation, and competitiveness, and has made recent progress.

The UK is recognised as an influential and innovative player when it comes to the development of law, regulations, and standards – notwithstanding the impact of Brexit on its ability to influence the approach taken by the world's largest single market, the EU.

The UK Government aspires to apply a similarly proactive and impactful approach to its regulation of the space sector. Including through active participation in the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS), the UK has long contributed to international efforts to develop legal, regulatory and normative frameworks to shape the evolution of space.[79] This includes being party to[80]:

- The 1967 Outer Space Treaty
- The Rescue Agreement
- The Liability Convention
- The Registration Convention.

[79] Butchard & Mills (2022).

[80] By contrast, the UK is not a party to the Moon Agreement, which expands on the 1967 Outer Space Treaty to address specific issues relating to activities on the Moon and other celestial bodies.

At the domestic level, the UK was 'one of the early pioneers to adopt national space legislation to regulate the space operational activities of non-governmental (private commercial) entities',[81] having introduced the Outer Space Act in 1986.[82] However, recognition of the Act's growing risk of obsolescence in the face of new technologies and the growth of the NewSpace economy, sparked a flurry of activity in recent years. Aiming to stay relevant and competitive, the UK has introduced a raft of new legislation, regulation, guidance, and institutional reforms, with developments including:[83]

- Creation of the UK Space Agency in 2010.
- Amendments to the Outer Space Act 1986 in the Deregulation Act 2015.
- Introduction of new primary legislation, with the Space Industry Act 2018 receiving Royal Assent in 2018 and entering into force from 2021, governing all space-related activities carried out in or from the UK (with the Outer Space Act 1986 still applying to overseas activities by UK entities).
- Designation of the Civil Aviation Authority (CAA) as the UK's space regulator, with effect from July 2021, alongside the continuing work of Ofcom as the UK's national spectrum regulator and representative for the International Telecommunications Union.
- Introduction of new secondary regulation, namely the Space Industry Regulations 2021, the Spaceflight Activities (Investigation of Spaceflight Accidents) Regulations 2021, the Space Industry (Appeals) Regulations 2021, and the Regulator's Licensing Rules.
- Publication of official guidance on a wide range of topics, including how to apply for launch operator, orbital operator, spaceport or range control licenses and the associated obligations, and how to assess environmental, security, or safety matters, address accidents, or make appeals.

These efforts reflect a wider policy ambition to promote the rapid growth of the UK space sector alongside sustainable exploitation of the space domain, as per the vision set out in the 2021 National Space Strategy.[84] As noted by one expert in space law, 'The Space Industry Act positively exploded the national space legislation scene, bringing with it 72 sections and 12 schedules, in contrast to the Outer Space Act [1986]'s 15 sections… [in turn] the new Space Industry Regulations effectively draw from their parent Act'.[85] As of May 2023, the CAA has reportedly issued some 343 new licences to companies working in the UK space sector, including the country's first spaceport and launch licenses; its pipeline of applications under review includes several additional UK spaceports and launch companies.[86] The CAA is also now monitoring more than 750 UK satellites in space, and funding technical research on relevant topics to inform development of future regulations and guidance, such as on the impact of suborbital flights on the health of passengers.[87]

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[81] Wheeler (2021).

[82] UK Government (1986).

[83] UK Government (2021); Wheeler (2021); Worthy (2023).

[84] UKSA, et al. (2021).

[85] Simmonds (2018).

[86] CAA (2023a).

[87] CAA (2023a).

In addition, the UK has launched consultations on several other issues and committed to issue further regulations or guidance on emerging space activities such as in-orbit servicing and manufacturing (IOSM) and active debris removal (ADR), expected by 2024 and 2025 respectively.[88]

5.1.2. Despite this flurry of recent activity, gaps remain – with new technologies and capabilities likely to further test the limitations of existing space regulation.

While the UK has made significant progress on space regulation in the last few years, some issues still need further consideration. These include a mix of ambiguous sections within existing regulations that might need clarifying ('non-liquet') and outright gaps (lacunae); in both cases, the lack of detailed answers on certain topics might be intrinsic, intentional features of space law and regulation, or unintentional and emergent over time, with technological progress unlocking new space capabilities and use cases that the original authors did not imagine at the time of writing.[89]

Emerging technologies such as those explored in Chapters 2-4 can place pressure on the regulatory framework in several ways, exposing possible gaps or areas of insufficient clarity. These include:

- Boosting the scale and diversity of activities in space, and the complex interactions between different technologies, activities and markets that were hitherto kept separate.
- Enhancing existing capabilities – either boosting safety and reliability, or, conversely, introducing new safety risks, environmental impacts or other externalities that need to be regulated.
- Creating entirely new use cases and markets, with unfamiliar risks and opportunities to shape.
- Providing new technical means of either enhancing or degrading regulators' access to evidence to inform licensing and other decisions (e.g., black box algorithms and non-deterministic AI would make it harder for regulators to validate and verify claims made about the safety of autonomous space systems, whereas advances in satellite surveillance and tracking could aid with monitoring and enforcement of national space regulations for UK spacecraft).
- Deepening cross-border linkages (e.g., through enabling sharing of multiple payloads within a single satellite bus; or promoting globalised supply chains for key enabling technologies), with all the associated jurisdictional complications that this brings.
- Creating a more 'congested, contested, and competitive' space environment, with a more complex ecosystem of space stakeholders, and thus more dependencies, vulnerabilities, and risks to mitigate.
- Testing the limits of regulatory competence by introducing novel areas of S&T for which resource-constrained regulatory organisations need find suitable technical expertise, models and data.
- Placing time pressure on regulatory policymaking, given the pace of technological and commercial innovation, and the need for regulators to make complex but timely decisions that balance several competing imperatives while dealing with deep uncertainty about the future (see Section 4.1.3).

[88] Worthy (2023).

[89] Johnson (2019).

5.1.3. Collectively, the technologies examined in Chapter 3 support the rollout of a series of space capabilities that demand near-term attention from regulators.

Developments in many of the technology areas examined for this report are already feeding into capabilities on or nearing the market. The proponents of such capabilities are thus vying for regulators' attention, especially as the UK Government seeks to achieve its 10-year vision for growing the space sector in line with the ambitions of the 2021 National Space Strategy. A literature scan and stakeholder workshop suggest some near-term regulatory issues meriting further consideration if the UK is to keep pace with technology.

Table 5.1 Possible near-term considerations for space regulation

Focus area	Examples of possible regulatory priorities, gaps, and issues
Embedding, maturing, and refining the new UK regulatory framework	• Continuing to develop bespoke regulatory approaches to retain UK regulatory thought leadership and competitiveness, encouraging Foreign Direct Investment (FDI) in the UK space sector.[90] • Continuing to routinise and streamline the licensing of launch, orbital operators, spaceports (for both vertical and horizontal launch), range controls, etc.[91] • Enhancing regulators' access to data from industry, including through data standards, increasing the ability to make informed assessments and to model potential risks and impacts from novel space technologies and capabilities.[92] • Driving down the financial and non-financial burdens on license applicants and regulators alike.[93]
Providing regulatory enablers for areas of major near-term growth	• Promoting Space Domain Awareness (SDA) and trusted sources of insight into what is happening, and why, in space, as a basis of monitoring and attribution of behaviours on orbit.[94] • Addressing safety and other risks associated with the increase in space tourism.[95] • Continuing to understand and mitigate the safety risks, debris generation and spectrum interference challenges, and insurance provisions associated with mega-constellations in LEO.[96] • Developing regulations and guidance to enable creation of a viable UK industry for active debris removal (ADR) and in-orbit servicing and manufacturing (IOSM), in line with wider UK investments and policy goals in this area, while also addressing the associated risks in terms of potential perception by some states of such dual-use capabilities as hostile or weaponised.[97] • Ensuring that insurance and third-party liability (TPL) provisions remain appropriate in a fast-changing space sector.[98]

[90] Wheeler (2021).

[91] Worthy (2023).

[92] Ligor, et al. (2023).

[93] Hawkins, et al. (2019).

[94] Retter, et al. (2023).

[95] Ligor, et al. (2023).

[96] Simmonds (2021).

[97] Worthy (2023).

[98] Worthy (2023).

Focus area	Examples of possible regulatory priorities, gaps, and issues
Addressing national security and resilience concerns	• Promoting norms of responsible behaviour more generally, building on the UK's leadership in the relevant UN Open-Ended Working Group, including in terms of establishing agreed norms for close-proximity missions, etc.[99] • Addressing the ambiguity over what constitutes a space weapon, given the dual-use nature of technologies, especially in the context of heightened geopolitical tensions more generally.[100] • Using regulation to help promote greater resilience of space systems and space-dependent services to deal with space weather and other natural hazards (e.g., outages caused by debris/collisions).[101]

Source: RAND Europe analysis (2023).

5.1.4. In the long-term, more ambitious use cases will require a similarly bold look at space law and regulation.

There are many regulatory gaps and ambiguities that will only become more pressing as technology progresses. As discussed in Chapter 3, these include specific tech-related gaps, e.g., developing suitable regulations for space-based solar power[102]; nuclear power sources[103]; biosafety in space[104]; geoengineering[105]; etc. It also means addressing more cross-cutting questions to shape the sector in the long-term. Examples emerging from the literature scan and stakeholder workshop held for the RHC study include:

Table 5.2 Possible medium- and long-term considerations for space regulation

Focus area	Examples of possible regulatory priorities, gaps, and issues
Governing a more expansive, diverse, and complex space ecosystem	• Streamlining licensing as many uses of space become more routinised and delivered at scale, while promoting international standards and collaboration between relevant agencies across jurisdictions.[106] • Addressing the inevitable need for robust Space Traffic Management (STM), backed by SDA, as the usage of space increases, (e.g., by means of a space-sector equivalent to the Chicago Convention, such as establishing an International Civil Aviation Organisation [ICAO] for space, creating a new UN specialist agency, or expanding the remit of ICAO beyond Earth's atmosphere).[107] • Moving beyond allocation of slots in GEO and regulating use of other strategically important locations within space, e.g., Lagrange Points, to avoid conflict and manage competition.[108]

[99] Retter, et al. (2023).

[100] McClintock, et al. (2021).

[101] Black (2018).

[102] Soroka & Kurkova (2019); Abashidze, et al. (2022); Pagallo, et al. (2023).

[103] US Nuclear Regulatory Commission (2023).

[104] Scott (2016); Rutter, et al. (2020).

[105] McClintock, McCormick, et al. (2023).

[106] RHC (2024).

[107] McClintock, et al. (2023); McCormick, et al. (2023).

[108] Byers & Boley (2022).

Focus area	Examples of possible regulatory priorities, gaps, and issues
	• Promoting spectrum sharing with new telecommunications technologies, refining ITU and Ofcom's approach to regulating spectrum use to encourage rollout of 6G+.[109] • Addressing questions around spectrum management and comms in cislunar and lunar space.[110] • Clarifying liability and other issues associated with spacecraft and other objects that originate from space-based manufacturing lines, e.g., using in-situ resource utilisation (ISRU), rather than having been launched from Earth (given the focus of so many clauses and obligations on launch countries in the 1967 Outer Space Treaty, or the Registration and Liability Conventions).[111] Similarly, considering any legislative or regulatory updates required for humans and animals born in space.
Managing safety risks at scale	• Clarifying the application of space law and regulations in situations involving machine agents (i.e., AI and autonomous systems), rather than humans (e.g., pilots on spacecraft, or launch operators), building on wider work on the governance of AI and autonomy across all sectors.[112] • Clarifying the status of astronauts as 'envoys of humanity' in the OST and the rescue obligations placed on other actors, especially as the spacefaring or space-based populations rapidly increase.[113] • Addressing growing need for rescue and/or law enforcement services in space, as the space-based population and the number and value of space-based assets and infrastructure increases rapidly.[114] • Addressing safety risks associated with megastructures in space (e.g., orbital habitats or industrial facilities, space-based solar power plants, etc.) and any transmissions (e.g., energy) to Earth.[115]
Securing the basis for innovation and growth	• Clarifying the application, or not, of the rule of non-appropriation and ensuring protections for intellectual property rights for creations and inventions arising from or in space.[116] • Clarifying the jurisdictional and information-sharing issues associated with crimes committed in or from space and providing enforcement mechanisms (including to address risk of space piracy).[117] • Clarifying property ownership, and resource access/mining/exploitation rights for asteroids, the Moon and Mars, and addressing associated risks to safety, security or economic stability (e.g., arising from distortionary effects on markets from massive windfalls from, say, asteroid mining).[118] • Addressing specific issues arising from settlement and exploitation of the Moon (conscious that the UK, and many other major spacefaring nations, are not [yet]

[109] Castro (2023).

[110] Dundas & Batty (2023); Foust (2023).

[111] Simmonds (2021).

[112] Pagallo, et al. (2023).

[113] Capoglu, et al. (2022).

[114] McClintock, McCormick, et al. (2023).

[115] McClintock, McCormick, et al. (2023).

[116] Hawkins, et al. (2019).

[117] Slapakova, et al. (2022).

[118] Johnson (2019); Simmonds (2021).

Focus area	Examples of possible regulatory priorities, gaps, and issues
	parties to the Moon Agreement).[119] This could include consideration of creation of a specialised UN agency or other international organisation for the purpose, such as an International Civil Lunar Organisation.[120]
Promoting sustainability and protecting the space environment	• Ensuring sustainable long-term use of space, in and beyond Earth orbit, and fostering a regulatory framework that promotes responsible long-term environmental stewardship.[121] • Ensuring regulations reflect consideration of minority group, global (e.g., including non-spacefaring nations in the Global South) and cross-generational perspectives and space equities.[122] • Promoting technical and procedural standards for space objects that enable activities such as ADR, ISOM, safe de-orbiting, etc., and promoting recycling and the creation of a circular space economy to reduce environmental impacts.[123]
Addressing humanitarian, ethical and other public concerns	• Addressing concerns of different communities over Dark and Quiet Skies (DQS), given the proliferation of satellites, space stations and even megastructures in orbit.[124] • Protecting sites of historical, cultural, religious or other significance in space (e.g., Apollo landing sites; non-terrestrial areas of outstanding natural beauty, etc.).[125] • Clarifying the application of International Humanitarian Law and the Law of Armed Conflict and developing a consensus on any necessary updates to reflect more extensive use of space, the dual-use nature of space technologies, and growing terrestrial dependencies on space infrastructure.[126]
Mitigating risks and dependencies between space and terrestrial systems	• Preparing for, and recovering from, any major future conflict that might occur in space out to 2040 or beyond; incorporating the lessons from this experience into international and national space law, regulations and standards to reduce the likelihood or impact of conflict reoccurrence.[127] • Incentivising or mandating technical and procedural steps that enhance mission assurance and promote resilience of space systems and space-dependent services more generally, including passive or active means of protecting satellites from hostile action, and reversionary modes.[128] • Addressing the increasing terrestrial dependencies on space across all sectors of the economy and mitigating the associated risks.[129]

Source: RAND Europe analysis (2023).

[119] Denny, et al. (2023); McClintock, McCormick, et al. (2023).

[120] Garretson (2022).

[121] McClintock, et al. (2021).

[122] Ogden (2022).

[123] New Space Economy (2023).

[124] ESO (2023).

[125] Walsh (2012).

[126] Klein (2023).

[127] Ligor & McClintock (2022).

[128] Black (2018).

[129] Retter, et al. (2023).

In general, the further into the future that one projects, the harder it becomes to distinguish between the 'space economy' and the 'economy', and thus between 'space regulation' and just 'regulation' – such is the likely depth and breadth of the linkages between space and almost all other sectors. This implies a growing need to embed consideration of the possible space dimension to all areas of policy, law and regulation, as humanity develops towards an 'integrated cis-lunar econosphere' across the course of the coming decades.[130]

5.1.5. As in any sector, the UK faces a series of trade-offs and dilemmas when deciding how to regulate space – these will only become more acute in future given the pace of change and the scale of potential risks and rewards.

There are difficult normative judgements for the UK to make when deciding how it wishes to address the regulatory gaps and ambiguities discussed above. The literature reviewed and workshop held for this study stressed how regulators must weigh a series of competing imperatives and make complex trade-offs[131]:

- How to make trades between competing goals around growth, safety, sustainability and security?
- How to balance risk versus opportunities, especially given the tendency of many policymakers and regulators to focus on minimising the former (especially when it comes to safety) ahead of maximising the latter (i.e., a cognitive bias towards considering risks of commission over risks of omission)?
- How to balance competition versus collaboration, recognising that the UK wishes to gain a strategic advantage through its approach to space regulatory policy, but also seeks to influence international allies and partners (including larger markets, e.g., the United States or EU), and shape global governance?[132]
- In a highly competitive space environment, how to attract investment and help UK space companies to scale, while also addressing national and economic security risks associated with FDI?
- How to promote efficiencies across UK and globalised space value chains, while mitigating challenges such as supply chains risks with access to critical minerals?
- How to avoid an international 'race to the bottom' on regulatory standards, and the risk of spacefaring organisations adopting the space equivalent of 'flags of convenience'?
- Where to focus the finite resources of UK space regulators, in terms of political bandwidth, personnel, funding, and capacity to engage with industry and other stakeholders?
- How to balance the desire for stability in the regulatory framework to give industry certainty and encourage private investment vs the need to evolve and adapt for the long-term? Where to pursue 'first mover advantage' for the UK on regulating novel tech and capability, versus where to learn from others' risk-taking and mistakes and pursue 'second mover advantage' as technologies mature?

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[130] Scott, et al. (2015); Black, et al. (2022).

[131] RHC (2024).

[132] RHC (2024).

Crucially, the research also emphasised the requirement for UK policymakers and regulators to look across the full toolkit of levers and enablers, not just regulation, and consider the international dimension that is so inextricably linked to outcomes at the national level. It is to these two themes that the final chapter turns.

6. Evolving the approach to space regulation

This chapter concludes the analysis for this report, by considering possible ways of better future-proofing the UK's national space regulation policy against emergent issues associated with rapid technology change. First, it discusses possible options for responding to the gaps and dilemmas outlined in Chapter 5:

- Discussion turns initially to national regulatory policy, considering both the regulatory and non-regulatory enablers of a more adaptive, future-proof approach to space regulation. A central theme that emerges is the need for continuous iteration, learning and adaptation, backed by participatory approaches and fora for dialogue and experimentation. This reflects the rapid pace of change expected in technology and in the space sector more widely out to 2040 and beyond. This can be contrasted with the comparatively nascent, untested nature of UK space regulation, much of which only dates to 2021, and constraints on regulators' access to resource, data, and people.
- Having explored the domestic dimension, the discussion moves to how and where the UK could benefit from shaping governance, law, regulation and standards at the international level. This reflects space's inherently shared and special status as the 'province of all [hu]mankind', and the requirement for global cooperation on governance issues to ensure future space safety, security and sustainability while avoiding a regulatory 'race to the bottom' that could cause everyone to lose.[133]

The chapter then concludes with a brief exploration of possible contributions that emerging technologies can make as enablers of space regulators and regulation. This reflects the positive – rather than merely disruptive – impact that advances in many areas of the Government's S&T Framework might have on the work of bodies such as the UK Space Agency, the CAA, Ofcom, DSIT, Department for Transport (DfT), Foreign, Commonwealth and Development Office (FCDO), MOD, Space Command and others tasked with various roles in shaping the future evolution of the UK space sector.

6.1. Addressing the domestic dimension

As outlined at the end of Chapter 5, a key finding from this short study is the need for the UK to consider the full toolkit of levers for shaping the outcomes of space regulation in the broadest sense: thinking beyond formal legislative and regulatory mechanisms, to also consider how these reinforce – or not – wider policy initiatives; standards; incentives; use of public procurement and R&D spending to shape markets and crowd-in private investment; formal and informal engagement with industry, including through clusters; skills initiatives; participation in international military, commercial or scientific partnerships; etc.

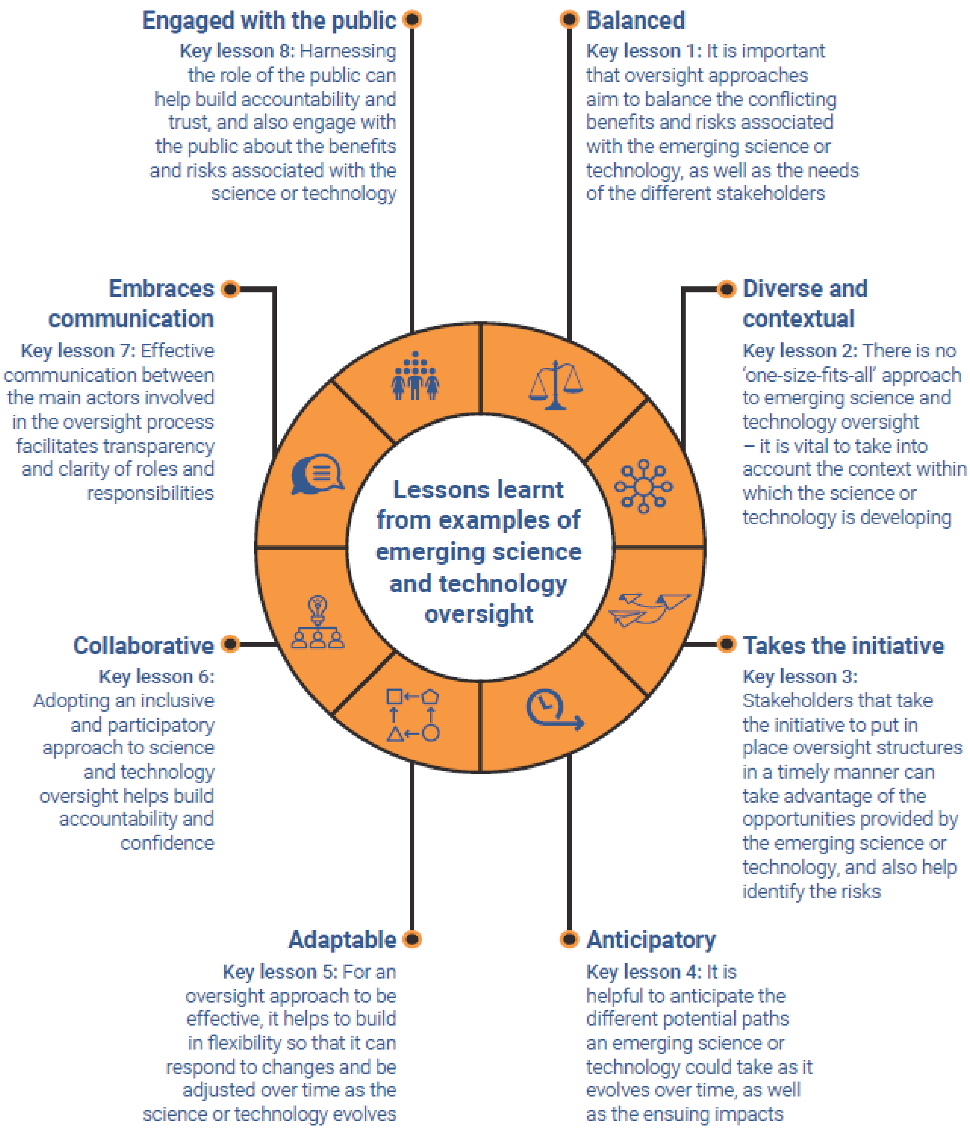
[133] Ligor & Matthews (2022).

The following sections briefly summarise possible regulatory and non-regulatory enablers.

6.1.1. Research emphasises the benefit of anticipatory, adaptive and participatory approaches to regulating sectors, such as space, undergoing rapid change.

While this short study for the RHC was not tasked with assessing and recommending how the UK *should* seek to regulate emerging space technologies and capabilities, prior RAND Europe research offers pertinent lessons from other sectors seeking to implement innovative regulatory approaches to deal with emerging technology (see Figure 6.1). These lessons emphasise the benefits of continuous learning, experimentation, dialogue and iteration. This involves creating safe spaces for testing out new technologies or capabilities, and working collaboratively across government, industry and other stakeholders to better model, predict and understand novel risks rather than stifling innovation for years until solutions can be fully prescribed.

Figure 6.1 Lessons from oversight and regulation of other areas of emerging technology



Source: Gunashekar et al. (2023).

Practical examples of approaches that have been applied in other sectors include:

- **Strategic foresight and anticipatory regulation:** This includes use of horizon scanning, scenario modelling and other forms of futures and foresight analysis to enable anticipation of possible directions of technology and capability development, and associated risks and regulatory options.[134]
- **Regulatory sandboxes:** An adaptation of the sandbox concept originally pioneered in the software sector, this creates a regulatory 'safe space' where industry can carry out limited tests of new technologies, products or services in a live market. While doing so, they are exempt from certain regulatory requirements, but contribute feedback throughout and upon exiting the sandbox, as do users and regulators. These inputs serve to inform development of new regulations as required. Prominent examples in the UK context include the Financial Conduct Authority's regulatory sandbox for fintech, or the CAA's programme for exploring innovative aviation technologies.[135]
- **Red Teaming:** This introduces aspects or formal and informal Red Teaming and pre-mortems to help identify potential technical or procedural deficiencies in emerging approaches to safety, governance or regulation of an emerging technology (e.g., as for foundation AI models).[136]
- **Participatory approaches:** This includes a range of structured methods for engaging a diversity of perspectives to inform development of regulation on emerging topics. This includes not only input from industry and the scientific community, but also engaging with other stakeholders such as non-governmental organisations or the public (e.g., via surveys, crowdsourcing, citizen juries, Delphi workshops, choice experiments etc.) to understand their preferences or projections for the future.[137]

Rolling out such innovative approaches requires clarity on the vision and risk appetite of government, and the desired balance between, say, economic growth vs safety or environmental impact. This necessitates an integrated approach across government, as per the ambition of the National Space Strategy, aided by a clear vision on the role that the UK wishes to play in shaping the long-term evolution of space governance and markets.[138] Clear policy guidance on the desired level of ambition/risk appetite would then enable trades across each of the dilemmas described in Section 5.1.5, exploiting tools such as outlined in the list above.

In addition to hard law, there is potential for soft law as a policy mechanism to provide a more flexible approach to emerging technologies than traditional regulation. Such an approach could include multi-stakeholder groups to discuss issues and ideal policies, while sandboxing is one tool that can be used to facilitate discussions between innovators and regulators to address concerns and develop solutions.[139] Informal norms can also be established to clarify expectations, with non-binding guidance provided to offer clarity and advice.[140] However, such soft law may lack enforcement power, which means that there is an

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[134] NESTA (2023).

[135] Gunashekar, et al. (2023); CAA (2023b).

[136] Hicks, et al. (2023).

[137] d'Angello, et al. (2021).

[138] UK Space Agency, et al. (2021).

[139] Morrison (2019).

[140] Morrison (2019).

ultimate need for additional hard regulation to mitigate the risks of unbounded commercialisation and technology growth in the space domain. Cultivation of a diverse toolkit of 'hard' and 'soft' regulatory levers could allow the UK to evolve its approach to regulating emerging space capabilities over time, as they mature and are better understood, without stifling innovation at the outset.[141]

6.1.2. Wider enablers could ensure a more effective regulatory regime, including bolstering access to funding, niche skills and data.

For regulation to be effective, let alone future-proof, regulators must themselves be match fit. The stakeholder workshop conducted for this study emphasised the need for regulators to have access to suitable funding, personnel with relevant expertise and skills, and data from industry and the technical community to inform their decision making. These demands will only increase as the space sector continues to grow both in scale and in the diversity of capabilities, use cases and markets that must be assessed and regulated. As such, there is a requirement for continued investment, and a long-term plan for developing the talent, data and tools needed to keep pace with likely increases in the size and complexity of regulators' workloads.

Similarly, prior RAND research on US national space regulation has emphasised the need to build regulatory readiness on the industry side. Research suggests that the regulatory readiness of the commercial space sector depends on five main factors: '(1) access to, and understanding of, the regulatory process; (2) security of regulatory support (i.e., the level of certainty of future regulations); (3) the effectiveness of the regulatory support for the technology (i.e., that regulations could be issued that would support both public safety and technology development); (4) environmental effects, costs and security issues related to the regulation; and (5) the ability to pass the regulation (i.e., political and social acceptability)'.[142]

To this end, ongoing efforts to reduce the bureaucratic burden and financial costs of engaging with UK space regulation, especially for small and medium enterprises, are welcome.[143] Examples of recent practical initiatives include offering more centralised, distilled guidance, refining the CAA website to aid usability and navigability,[144] and examining other ways to streamline process and eliminate frictions.[145]

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[141] d'Angelo, et al. (2022); Gunashekar, et al. (2023).

[142] Ligor, et al. (2023).

[143] Worthy (2023).

[144] Daniels (2023b).

[145] For example, under the Space Industry Act 2018, obtaining an Orbital Operators Licence from the CAA, a Permanent Earth Station licence from Ofcom and the ITU, and potentially an export licence can be a significant burden on time and resources. This fragmented process requires identifying the appropriate regulators and completing separate application processes, potentially leading to delays in launches and the diversion of resources and labour away from technology development. As another example, during a recent Science and Technology Committee hearing, it was revealed that some of the satellite customers onboard the failed 2023 Virgin Orbit flight criticised the regulatory process, which was led by CAA, for being slow, excessively bureaucratic, and risk averse. The delays caused by the CAA, coupled with the launch failure, resulted in Space Forge falling six months behind its competition in the race to be the first company to bring a satellite back down to Earth, despite initially being six months ahead. One representative stated that the cost of licensing their satellite for launch was higher than the actual cost of launching it.

6.2. Addressing the international dimension

6.2.1. Research emphasises the inextricable linkages between the domestic and international dimensions of space law and regulation, and overall outcomes.

Space is inherently a global concern, affecting not only spacefaring nations but also terrestrial users of space services across all nations and sectors. Similarly, the scientific papers examined in the bibliometric analysis for this study, the novel S&T developments identified in the horizon scanning, or the discussions captured through literature and the discussions at the stakeholder workshop all reflected the vital role that cross-border collaboration plays in space value chains and thus also space governance.

As such, future development of UK national space regulation should be understood as part of a wider effort to shape the evolution of the space domain through use of both domestic and foreign policy levers. The UK has considerable diplomatic clout, relationships and networks to draw upon, in this regard. These include bilateral partnerships with individual nations; minilateral frameworks, such as participation in CSpO, the Artemis Accords, ESA, or NATO; and the UK's leading role within global institutions, such as the UN (building on the UK's recent experience leading on the OEWG on responsible space behaviours).

As discussed in Chapter 4 and 5, emerging technologies and space capabilities pose a series of regulatory challenges that can only be addressed at the international level. Examples raised in this report have included:

- Questions over the future of the 1967 Outer Space Treaty in a fast-changing space domain, amidst mounting calls for it to be updated or replaced.
- Unresolved debates among states over what constitutes irresponsible behaviours in space, or how best to manage thorny topics such as preventing an arms race in outer space (PAROS) in the absence of basic definitional agreement on what constitutes a 'space weapon', 'space militarisation', 'peaceful uses' or the 'province of all mankind'.
- The lack of a space equivalent to the International Civil Aviation Organisation, or an alternative agency or governance model for space to address issues such as STM.
- A lack of international consensus on how to manage risk, or share in the rewards, of future settlement and exploitation of the Moon, Mars and other celestial bodies.

To shape the international community's approach on the above, and the myriad other issues facing global governance of space, the UK should employ a mix of deterrence and soft power levers, working closely with allies and engaging less traditional partners. This includes reaching out to nations with more limited spacefaring history, and seeking to compete against Chinese, Russian and other hostile attempts to influence such countries against the UK's preferred approach – as was the case around the UN OEWG. The collective bargaining power of non-traditional spacefaring nations, particularly developing countries, remains underestimated, though there is potential for such efforts to challenge space norms before they crystallise in international space law.[146] The UK is well-placed to convene, broker, guide and inform such initiatives to ensure wider participation and equity in the spacefaring community. Equally, there is also a need to bring

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[146] Ogden (2022).

in industry, academia and civil society organisations to inform international debates – the input of such actors to the OEWG initiative was recognised by states as an important and beneficial way of bolstering space literacy for officials, especially from non-spacefaring nations.[147] There is opportunity for these objectives to be captured more expressly and concretely in future iterations of the National Space Strategy.

Of course, space governance cannot be insulated from wider geopolitics. This is only likely to be more true in future, given the increasing interlinkages between space and all sectors – including defence and national security – projected out to 2040 and beyond as a result of the emerging technologies and space capabilities discussed in Chapter 3 and 4. As such, further efforts are needed to build trust, identify 'quick wins', and resolve the broader tensions that ultimately stifled efforts to achieve international consensus on the OEWG's findings.[148] This should include exploration of novel confidence-building measures, alongside unilateral declarations (such as the self-imposed moratorium imposed by the United States, the UK and various allies on testing of direct-ascent ASAT missiles) and deterrence measures.[149] Regulatory efforts may need to take into consideration wider UK security efforts, particularly with regard to deterrence of adversarial escalation through the projection of UK soft and hard power. There are also opportunities to further explore lessons from the evolution of law, regulations and norms in other domains to inform approaches in space.[150]

6.3. Harnessing technology to enable more effective regulation

Finally, it is possible to turn the premise of this short study on its head: considering not how emerging technologies might pose new challenges for space regulation, but rather how they might provide regulators with new tools for delivering their mandate. UK space regulators could benefit from further exploring the potential applications of AI, ML, data analytics, and modelling and simulation technologies to help them in building an evidence base for regulatory and licensing decisions – including to model the possible impact of different regulatory design choices on future outcomes in terms of markets, risk and policy outcomes.

As outlined in a previous UK Government paper on the use of emerging technologies to support regulation, however, development and implementation of new data-sets and tools requires a problem-focused approach, access to suitable funding and SQEP, including technical skills, feedback loops to capture user feedback and iterate designs and functionality, and the ability to absorb innovation and scale up successful pilots across the regulatory organisation in question once a given tool or technology has proven its value.[151] All of this is easier said than done, especially in a resource-constrained and risk- or change-averse setting. This speaks again, then, to the need for regulators to not only seek to promote and incentive innovation externally (i.e., within the UK space economy), but also in terms of their capacity to learn, adapt and drive or absorb innovation internally (e.g., within the CAA, Ofcom, UKSA etc.). This is hard, but vital if they are to fulfil their stated ambition to make the UK a thought leader on innovative approaches to space regulation.[152]

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[147] Black (2022).

[148] Hitchens (2023).

[149] FCDO & UK Space (2022).

[150] McCormick, Ligor & McClintock (2023).

[151] BEIS (2020).

[152] Mazzucato (2021); Wheeler (2021).

7. Conclusion

As well as understanding emerging technologies in themselves, there is a need for ongoing horizon scanning and research to understand how these might translate into new space capabilities, and thus into use cases, markets and behaviours that require some form of regulation. This independent report for the RHC has sought to respond to this demand, within the constraints of a one-month study. It has explored the potential implications of emerging technologies for space capability development, across both the upstream and downstream segments of the space economy and in the long term and short term, while identifying what this all means for future space regulation.

However, this research is not comprehensive and there will be 'unknown unknowns' in terms of technology advancements, or emergent risks or opportunities, which cannot be anticipated now, and which will need to be considered by regulators further down the line. As such, there will be a need to continuously update and revisit expected benefits, costs, risks and timelines. To this end, there is a general need for boosting the use of horizon scanning and ensuring space literacy across the regulatory ecosystem and UK Government.

This study has also considered the opportunities and risks for the UK, identifying its unique position as a relatively important spacefaring nation, with the scientific and diplomatic clout to define global norms and standards, as well as the potential to emerge as a major regulatory player within the space domain. As a key actor in international fora such as the ESA, NATO and the UN, Britain is well-placed to play the role of diplomatic 'broker', bringing other players to the table. However, a lack of SQEP and resource could hamper efforts in this domain, and the risk of militarisation and conflict in space could prove disruptive to harmonious exploration and collaboration. There will be an ongoing need to better understand how the UK can overcome these obstacles and establish a roadmap to identify long-term solutions to these problems.

The UK's regulatory process also needs to be agile enough to adapt to the rapid tempo of innovation. This report outlines some of the approaches to regulation, though it is likely that there will be a need for a combination of approaches through both 'hard' regulation and 'soft' guidance and sandboxing initiatives to provide a more agile regulatory framework. There is scope for further research, for example to examine the regulatory approaches to AI or other tech to understand existing good practice and lessons learned. The approaches adopted by other countries or in other sectors could also help provide insight to UK regulators.

Finally, this study has emphasised the benefits of a mixed-method, multidisciplinary approach. As humanity expands into space, there will be a need for deeper and meaningful engagement across multiple perspectives about how to best utilise resources, interact with other space actors and engage with the space environment. The multifaceted approach and stakeholder engagement employed as part of this short RAND study – and the wider RHC and DSTI reviews into which it feeds – have aimed to reflect this model in microcosm.

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Annex A. Methodology

This annex summarises the research methods employed for this short study.

A.1. Scoping review

The research team commenced the project by conducting a preliminary scoping review of publicly available sources to inform the initial steps of the study. The scoping review helped establish a delivery plan in consultation with the RHC and develop an understanding of the existing state of space technologies and regulatory documentation, providing the basis for subsequent data collection and analysis. The scoping review involved initial scoping of current and planned UK regulation of space activities, including orbital regulation and spectrum management, as well as the anticipated future uses of space and emerging technologies out to 2040. Developing an understanding of the current UK regulatory environment for space technologies also helped in the early identification of current or anticipated regulatory gaps.

A.2. Data collection

The second stage of this study included data collection and analysis activities to generate preliminary findings on emerging space technologies across the five priority areas and beyond, as well as identification of breadth and depth of current literature. The research team employed two data collection methods, supported by RAND Europe's Centre for Futures and Foresight Studies (CFFS):

- **Bibliometric analysis and topic modelling:** The use of bibliometric analysis and topic modelling techniques provided a high-level survey of the science and technology (S&T) literature at the intersection of the space sector and the identified critical technologies.
- **Horizon scanning:** The team conducted a review of the RAND Europe Centre for Futures and Foresight Studies' existing horizon scanning database of S&T signals.

The resulting set of summary statistics and charts and horizon scanning items provided a holistic overview of the relevant S&T literature and emerging signals to inform the later stages of this research. The two data collection methods are outlined in further detail in the following sections.

A.2.1. Bibliometric analysis and topic modelling

The bibliometric and topic modelling analysis was designed to:

- Gain a general understanding of the overall scope of research associated with space flight and exploration and the in-orbit economy.
- Gauge the relative importance of identified critical technologies within the space research literature.
- Test whether additional critical technologies should also be explored.
- Identify key sub-fields of research associated with each critical technology intersection and how these may have changed over time.

The approach covers two main steps: bibliometric data extraction and processing, followed by machine automated topic modelling to identify clusters of research activity. Bibliometric data was filtered and extracted from OpenAlex, an open-source data product.[153] The open-source nature of OpenAlex gives transparent access to the underlying metadata and the networked connections between scholarly papers, authors, institutions and journals. OpenAlex currently indexes over 240 million journal articles and updates daily with new publications and citations.

The metadata associated with each research paper in OpenAlex includes tags to a hierarchical taxonomy of research fields. Taxonomy items were manually identified that relate to the space sector, including flight, exploration, and the in-orbit economy, and each of the critical technologies.[154] These tags, along with publication window from September 2017 to September 2023, were then used to efficiently filter the vast volumes of research papers available in OpenAlex to create 8 separate datasets: one covering the whole of space sector research and another for each critical technology: the 5 original technologies (artificial intelligence, quantum, future telecommunications, semiconductors and engineering biology), plus materials science and energy & propulsion. Each dataset contains detailed metadata about each paper including the full paper abstract.

Topic modelling techniques were then used to reveal clusters of research activity based on the language used within each abstract. This approach can reveal patterns potentially missed by simpler keyword or taxonomic mapping. For example, the tendency for certain keywords to come in and out of popular usage over time can be countered by a richer search for semantic similarity across abstracts.

The topic modelling involved several stages:

- **Extract abstract embeddings:** The first step involved converting each abstract into a numerical representation using a sentence transformer designed for English-language semantic similarity tasks.

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[153] As of 22 February 2024: https://openalex.org/

[154] Due to particularly small intersections, semiconductor technology was broadened to cover electrical and electronic engineering, and engineering biology was interpreted to cover synthetic biology, biotechnology, bioinformatics and biomedical engineering.

- **Dimensionality reduction:** Since the embeddings were created in a high-dimensional space incompatible with clustering algorithms, a technique called Uniform Manifold Approximation and Projection (UMAP) was used to collapse the embedding representation down just three dimensions, while preserving information about both the local and global structure that is needed to create clusters.
- **Cluster reduced embeddings:** A clustering technique called HDBSCAN was then used to find clusters of abstracts that sit closely to each other in the three-dimensional embedding space.
- **Create topic representations:** The first step toward creating cluster representations, or labels, involves calculating 'bags-of-words' by merging all abstracts in each cluster into single documents and counting how often each word appears. Common stop-words (e.g., 'the', 'at', 'and', etc.) are ignored to help focus on words that reflect the nature of the clusters. A model called class-based TF-IDF was then used to identify the most important words within a cluster normalised by its size and relative to all the other clusters, i.e., the words that best represent the cluster.
- **LLM assisted labels and descriptions:** Keyword labels from the previous step are useful but are not easily read. As an alternative, a large language model (LLM) was used to convert the keyword representations into simple topic labels and intuitive descriptions.

The bibliometric and topic modelling analysis provided insight into the scope of research relating to the space sector, and in particular its intersection with critical technologies, which helped guide the research presented in this report. There are opportunities to extend this type of research further to support regulatory decision-making and wider government space efforts in the future, for example:

- Dynamic topic modelling techniques combined with network analysis could help reveal how different fields of research are evolving over time, providing deeper insight into the likely direction of future research.
- Large Language Models, in addition to providing topic labels and general descriptions, can be used to summarise large batches of abstracts and research papers to provide a detailed understanding of the work being carried out within different clusters of research.
- Similar methods can be applied, for example, to patent documentation. This could provide another lens into emerging science and technology at the intersection of space and critical technologies and provide insights into how other governments are thinking about future space regulation.

A.2.2. Horizon scanning

The team conducted a review of RAND Europe's existing horizon scanning dataset of S&T signals. Since 2018, RAND Europe has written over 1,750 horizon scanning S&T signal abstracts covering a wide range of subjects including the five critical technologies, informing prior studies for sponsors such as the Defence Science and Technology Laboratory, and the UK Space Agency.

This stage of the study focused on identifying signals within this dataset that could have implications for the space sector. The study team mapped the five critical technologies to the existing classifications to find signals relating to each technology. Keyword searches were used to identify any pre-existing associations with the space sector. The team then conducted an examination of critical technology signals, drawing on the database entries' assessment of uncertainty and likely timeframes involved, such as through identification of TRLs. The horizon scanning summarised specific and impactful examples of emerging technologies across each of the five priority technology areas, with viability of implementation out to 2040.

A.3. Stakeholder workshop

An RHC-facilitated workshop on 16 November 2023 brought together experts and practitioners to discuss the top emerging technologies with application to space out to 2040 across the five priority areas, as well as implications for the UK and current or anticipated regulatory gaps. RAND Europe produced a slide deck to provide preliminary insights gained from this research, highlighting key technologies and their intersection with space, as well as the resultant space capabilities. The subsequent discussion with diverse groups of experts and regulators generated lively debate around four potential scenarios and implications for the UK, as well as regulatory considerations. RAND Europe researchers participated in the conversations and noted emerging findings on regulatory gaps, as well as the technologies of interest to guide further stages of this research.

A.4. Final targeted research and reporting

The final stage of this research included a deeper dive into the relevant literature to supplement previous findings and to respond to priorities and feedback identified in the Space Futures workshop. The research team conducted a literature scan of publicly available sources to initiate a deep dive into the five priority technology areas and beyond.

To identify relevant sources for inclusion in the literature scan, the research team used three strategies:

- Identification of relevant sources and existing RAND research through RHC and RAND's existing knowledge of the research landscape.
- Boolean searches with a combination of key-words through relevant open-source databases, such as Google Scholar, and the subscription access provided by RAND Knowledge Services.
- 'Snowball searching' consisting of identifying relevant sources through the reference lists of already identified literature.

This desk-based research enabled a deeper understanding of key emerging space capabilities and the implications, opportunities, and risks for the UK. This fed into generation of a draft report, which was shared with RAND Europe Quality Assurance (QA) reviewers, as well as the RHC and DSIT, for feedback.

Annex B. Technology Intersections

This annex outlines a brief discussion of each technology area included in this study, covering:

- Near-term technology trends (based on bibliometric analysis and a literature scan)
- Possible developments out to 2040 (based on horizon scanning)
- How such developments could translate into new space capability and use cases
- Associated considerations for future space regulation policy in the UK.

B.1. Critical Technology 1: Artificial intelligence, autonomy, and robotics

Artificial intelligence (AI) refers to machines that can perform various functions independently, simulating human intelligence. AI is a critical technology as it can help address complex problems that are difficult or impossible for humans to solve on their own. It can also help automate repetitive tasks, improve situational awareness and decision-making, especially under tight timeframes, and provide insights into large amounts of data.[155]

Related fields of S&T investment and activity include machine learning (ML), autonomy, human-machine teaming (HMT), and robotic systems of varying levels of sophistication, automation, and capacity for collaboration (e.g., multiple systems cooperating in a swarm, or a mothership-and-drone configuration).

[155] Menthe, et al. (2021).

B.1.1. Near-term technology trends

Bibliometric analysis and a literature scan highlight current focus areas for scientific research, including:

- Machine learning
- Cognitive computing
- Expert systems
- Fuzzy logic
- Genetic algorithms
- Knowledge representation
- Robotics
- Swarm intelligence
- Virtual and Augmented reality.

Of the five critical technologies identified in the Government's S&T Framework, AI has the largest number of intersections with the space domain in the academic literature, with 26,700 of the 122,100 scientific publications on space-related S&T in the last five years examining AI and ML in some manner. Areas of intersection include:

- Mission planning
- Spacecraft thermal control
- Attitude control systems
- Optimal trajectory planning
- GNSS Positioning systems
- Space robotics
- Space debris navigation
- Crop classification techniques
- Environmental monitoring
- Wildfire detection
- Image enhancement.

B.1.2. Possible developments to 2040

Horizon scanning suggests a range of possible areas for future development, including:

- Automated launch and return of satellites
- Automated design of spacecraft
- Improved predictive maintenance and repair
- Automated navigation of spacecraft
- In-orbit servicing and refuelling through automated docking
- Automated end-of-lifecycle disposal and recycling of parts.

Of note, AI is currently an area of significant publicity, hype and frantic investment by both state actors and private sector tech giants.[156] However, it is important to emphasise that the fields of AI, autonomy and robotics have previously seen similar bursts of optimism over the potential for rapid progress, only to slide into more pessimistic projections of an impending 'AI winter'. As such, experts in the field remain deeply divided over the likely pace and impact of future advancements, with particularly intense debates ongoing over when, if at all, Artificial General Intelligence (AGI) will be achieved, as well as which approaches to AI and ML hold most long-term promise.

B.1.3. Impact on space capability and possible use cases

Fast-paced developments in AI suggest that its intersections with the space domain will also become increasingly prevalent out to 2040. In space settings, AI can already analyse large volumes of data collected by space objects, assist with fuel optimisation, spacecraft design, manufacturing and operations, including autonomous navigation, automation of engine operations and docking. It can also help to reduce the risk of machine malfunctions, substitute human decision-making, and improve mission success, and in some cases safety.[157]

Looking to the future, AI has the potential to help fuse, clean, analyse, prioritise and make sense of ever larger volumes and variety of data collected by or relevant to space objects and infrastructure. Similarly, advances in autonomy reduce the requirement for a human to be 'in' or 'on the loop' for decision making – of particular use when operating space assets in locations or for tasks where remote control is either unnecessary, a risk, or simply not possible (e.g., due to latency, or threat of jamming), and/or where

[156] This has been precipitated by, inter alia, the rapid progress in the capabilities of and consumer applications for LLMs; a series of high-profile corporate partnerships and investments in AI companies (e.g., Microsoft and Alphabet in OpenAI, Amazon in Anthropic); government initiatives to set guidelines for responsible development of foundation models and to invest in the associated compute; and public debates over AI safety and societal impact, including at the world's first AI Safety Summit hosted by the UK at Bletchley Park in 2023. This recent burst of activity has prompted a broad spectrum of responses, ranging from predictions of an impending singularity, through to concern over the existential threat of AGI.

[157] Marr (2023).

deploying crewed spacecraft would be unsafe or technically and financially impractical.[158] Progress in AI and robotics, meanwhile, is unlocking a wide range of potential new functionality for space systems and infrastructure, as well as helping automate the underpinning manufacturing base and to optimise supply chains within the space industry, in turn supporting the roll-out of Industry 4.0 concepts through more of the space-related value chain.[159]

Examples of potential impacts on space capability development across the upstream and downstream include:

Upstream:

- Insights from AI will help to unlock new design and maintenance approaches for space assets, increasing their performance, efficiency, safety and resilience, boosting value-for-money across the capability lifecycle.
- AI will increasingly help to assist with spacecraft design, manufacture and operations (e.g., autonomous navigation and docking), as well as continuous modelling of digital twins for both terrestrial and space-based systems, helping to predict faults, optimise sensor and network performance, conserve energy, etc.
- Relatedly, advances in autonomy and robotics promise to provide space systems with new hardware capabilities (e.g., enabling ADR, refuelling and in-orbit servicing in the medium-term, or the establishment of automated resource-extraction and manufacturing complexes in the longer-term).
- Autonomous and robotic systems are already used extensively in space exploration (e.g., probes, rovers); further advances could support development of orbital, cis-lunar, Moon or Mars settlements.

Downstream:

- The use of AI and ML to make sense of space data can benefit a range of downstream industries and activities, including Earth observation (EO) for agriculture, transportation, logistics, finance, telecommunications and other purposes (e.g., environment, land use, or climate and weather monitoring and modelling). This, in turn, can lead to the creation of valuable new markets (e.g., AI-enabled, space-based climate monitoring could support development of new financial products associated with carbon net zero and the green transition).
- The use of AI and ML, along with edge computing, can also help to reduce the amount of data that needs to be transmitted between satellites and ground stations, e.g., by automatically deleting cloudy or otherwise not usable satellite imagery, thereby optimising energy, storage, and bandwidth usage, and reducing costs.[160]

[158] Scharre (2018).

[159] Black, et al. (2022).

[160] ESA (2023).

- The ability to collect and analyse data from space-based sensors will be crucial not only for myriad civilian purposes, but for national security users as well, enabling monitoring of potential threats, decision support tools for military command and control, and satellite connectivity for uncrewed systems.

Equally, advances in these technology areas are likely to enable both the proliferation of, and new ways of mitigating against, different threats, risks and hazards that can disrupt or destroy space assets and undermine the resilience of space-dependent infrastructure, networks, and services. For example, this could include use of AI for modelling and predicting space weather that could endanger space objects or astronauts; automating cyber defences for space systems and networks; or, conversely, new automated means of launching kinetic or non-kinetic attacks on satellites.

B.1.4. Considerations for future space regulation

While the focus of UK space regulation policy is on regulating capabilities, uses cases and markets, rather than individual technologies, specific regulatory considerations arising from advances in this area include:

- Mitigating safety risks associated with AI and AGI, agnostic of the space domain.
- Addressing legal, regulatory and ethical issues around autonomy and automation, especially in situations involving risk to life or the use of force (e.g., space weapons).
- Clarifying norms of responsible behaviour for AI- and robotics-enabled dual-use capabilities (e.g., ADR) that could be interpreted as hostile, with transparency and confidence-building measures to avoid accidental escalation.
- Clarifying liability and insurance for errors or harmful actions by machine agents.
- Conversely, minimising risk of human error in critical missions or tasks using AI.
- Addressing concerns over privacy and bias and preventing the misuse of sensitive data collected by or about space systems.
- Addressing the disruptive impacts of AI and automation on space-related industries, markets, jobs and wealth distribution.
- Mitigating cybersecurity risks to robotic and autonomous systems, and AI training data.
- Addressing challenges around verification and validation (V&V), especially for 'black box' and/or non-deterministic AI systems.
- Ensuring standards and interoperability.
- Addressing proliferation risk (both of AI and from use of AI to spread other space technologies).

B.2. Critical Technology 2: Telecommunication technologies

Telecommunication is the transmission of information by various types of technologies over wire, radio, optical or other electromagnetic systems. It has evolved significantly over the years, from traditional landline phone calls to the internet, mobile networks, and is now increasingly dependent on space-based assets and capabilities. Future telecommunications include a range of technologies such as space-based global broadband communication and web services, space laser communication technology, flexible satellites, quantum-encrypted communications, electromagnetic spectrum management, in-space communications relay, satellite backhaul and space-based data centres.[161] These technologies enable the transmission of information between multiple locations through electrical signals or electromagnetic waves.

B.2.1. Near-term technology trends

Bibliometric analysis and a literature scan highlight current focus areas for scientific research, including:

- 5G Networks
- Internet of Things
- Cloud Computing
- Edge Computing
- Blockchain
- Cognitive radios
- Radar systems.

Of the five critical technologies identified in the Government's S&T Framework, Telecommunications has the second largest number of intersections with the space domain in the academic literature, with 22,900 of the 122,100 scientific publications on space-related S&T in the last five years examining telecommunications in some manner. Areas of intersection include:

- Precision, accuracy, and functionality of global navigation satellite systems (GNSS).
- Antenna design and performance.
- Impact of ionosphere on GNSS.
- Non-orthogonal multiple access (NOMA) schemes.
- Free space optical (FSO) communication.
- Earth observation applications.

B.2.2. Possible developments to 2040

Horizon scanning suggests a range of possible areas for future development, including:

[161] Black, et al. (2022).

- Space-based data centres
- All-in-one chip enabled Internet of Things
- 6G+ communications
- Flexible satellites that can be repurposed post-launch.

B.2.3. Impact on space capability and possible use cases

The space sector plays a crucial role in the development and deployment of telecommunication technologies. As options for space-based internet connectivity become mainstream, facilitated by vast networks of LEO satellites, the future of telecommunications will increasingly be intertwined with advancements in the space sector, while the downstream applications enabled by future telecommunications will likely transform many aspects of our lives.

Future telecommunication technologies have the potential to revolutionise the way we communicate and access information. Telecommunication technologies can be used for space-based technologies by terrestrial transport systems and for intra-space transportation and traffic management.[162] Furthermore, future telecommunications technologies can enhance satellite communication by enabling faster data transfer, more secure communication, and better spectrum management.[163] They can also facilitate development of space-based data centres, offering reduced latency, increased security and improved energy efficiency.

Developments in the various areas of telecommunications also mean that communication is becoming increasingly reliant on space-based technologies. These developments bring many opportunities and advantages, such as better connectivity, greater data upload and download speeds, improved coverage and more secure communication. On the other hand, increased reliance on space-based assets for communications could pose risks if there are disruptions to the space-based infrastructure through adversarial interference or orbital debris.

Examples of potential impacts on space capability development across the upstream and downstream include:

Upstream:

- The integration of AI/ML into telecommunication technologies will focus on network optimisation, predictive maintenance and energy efficiency, for example.[164] These advances will both drive costs down and improve technical capabilities including reduced latency.
- Quantum communication uses quantum physics principles to provide secure, encrypted communication.[165] Satellites will be used to establish long-distance quantum communication links, opening applications that require high security and extended coverage, such as autonomous vehicles and military technologies.

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[162] Black, et al. (2022).

[163] Black, et al. (2022).

[164] ESA (2023).

[165] Martin, et al. (2021).

- Space-based assets will become integrated into an Internet of Things in space.[166] This interconnectivity will enhance navigation and communication, improving the monitoring and collection of data about spacecraft, the Earth and beyond.
- Flexible satellites that can be reprogrammed once in space offer the opportunity to respond to changing demands over time.[167]
- With the growth of data-intensive technologies like AI and IoT, there's increasing demand for data storage and processing. As a greater share of this data is either generated in or transferred through space, there will be greater demand for space-based data centres, that could leverage abundant solar power resources and natural cooling.[168]

Downstream:

- The advent of Low Earth Orbit (LEO) satellite constellations, such as those launched by SpaceX's Starlink project, promises to provide high-speed, low-latency internet access globally.[169] By 2040, we could see a fully-fledged 'internet from space', providing reliable, high-speed internet access even in remote areas.
- As the internet from space expands, so too will the Internet of Things (IoT). By 2040, we could see a fully connected world, with billions of devices communicating with each other, transforming manufacturing, agriculture, healthcare and transportation industries among others. IoT's growth will require robust and extensive network coverage, that space-based infrastructure has the potential to provide.
- The use of 5G coverage from space enables improved satellite communication, data transfers, remote operations and improves network resilience.[170] Similarly, 6G+ communications will help realise new business models and even more advanced downstream technologies.[171] This could include immersive technologies such as virtual reality (VR), augmented reality (AR) and mixed reality (MR) that will likely require high-speed, low-latency networks to function effectively.

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[166] Kua, et al. (2021).

[167] UK Space Agency (2021).

[168] Thales Alenia Space (2022).

[169] Marquina (2022).

[170] ESA (2023).

[171] Nguyen, et al. (2022).

B.2.4. Considerations for future space regulation

While the focus of UK space regulation policy is on regulating capabilities, uses cases and markets, rather than individual technologies, specific regulatory considerations arising from advances in this area include:

- Mitigating safety risks associated with reliance on space-based telecommunications assets, including exposure to space weather and adversarial attack.
- Addressing legal, regulatory and ethical issues around military technologies enabled by space IoT, including dual-use or reprogrammable satellites.
- Mitigating safety risks associated with orbital debris exacerbated by a potential proliferation of LEO satellites.
- Clarifying liability, jurisdiction, and insurance for data exfiltration and other forms of cyber-attack involving space-based assets.
- Mitigating risks associated with highly secure quantum communication (i.e., information that cannot be gathered by intelligence agencies.)
- Addressing the disruptive impacts of space-enabled 6G+ communications on industries, markets, jobs and wealth distribution.
- Mitigating cybersecurity risks to IoT in space.
- Addressing challenges around competition and monopoly of space-based internet service provision.
- Ensuring standards and interoperability.

B.3. Critical Technology 3: Quantum technologies

Quantum technologies refer to technologies resulting from the quantum effects of quantum mechanics.[172] Quantum technologies include quantum computing,[173] quantum sensing, quantum simulation, quantum measurement and quantum materials. Quantum technologies are essential as they have the potential to revolutionise computing, communication, navigation, encryption and sensing. In the space sector, these technological developments could be applied to improve communications and operational efficiency.

B.3.1. Near-term technology trends

Bibliometric analysis and a literature scan highlight current focus areas for scientific research, including:

- Quantum hybrid optimisation applications
- Quantum sensing technologies
- Quantum interferometry
- Data security and quantum networks
- Secure quantum communication technologies, including quantum key distribution (QKD)
- Quantum error correction.

The bibliometric analysis indicated that out of the five critical technologies the Government's S&T Framework, the third largest number of studies intersecting with the space domain were produced in the field of quantum computing. More specifically, the bibliometric analysis and literature scan identified 21,800 articles published since 2017 on topics relating to the application of quantum computing in the space domain. These applications include:

- Space debris removal
- Design and implementation of space control systems
- Satellite communications
- Navigation and positioning systems
- Calibration of radiometric sensors
- System reliability and failure analysis focusing on spacecraft systems
- Atmospheric gas monitoring
- Spacecraft power systems.

[172] Ibaraki (2022).

[173] Quantum computers use qubits and exploit quantum properties like superposition and entanglement that both significantly accelerate the computer's data processing speed. Superposition means a qubit is a mix of 0 and 1 but collapses into a specific state when observed, whilst entanglement is when particles become correlated, so measuring one determines the state of the other, even at large distances. Source: Gunashekar, et al. (2022).

The literature scan also indicates that quantum technologies will have a more direct role in Earth observation systems. For instance, satellite communication will increasingly use quantum key distribution (QKD) to generate and share encryption keys to enhance the security of data transmission.[174] Further, quantum sensors, such as quantum gravimeters and atomic clocks, could be used to improve the precision, and quantum computing has the potential to analyse Earth observation data more efficiently.

B.3.2. Possible developments to 2040

In the coming years and decades, quantum computing will have various applications ranging from big data analysis, weather forecasting, transportation engineering, renewable energy, healthcare and pharmaceuticals. The horizon scanning and literature scan conducted by the research team suggest the following developments out to 2040:

- New scalable and stable quantum hardware
- Quantum-safe cryptography
- Fault tolerant quantum computing
- Quantum radiofrequency sensing
- Commercialisation of quantum computing
- Quantum internet
- Space-born quantum magnetometry.

While significant advances are being made in the field of quantum technologies, some challenges remain, mostly stemming from limits to our understanding of quantum mechanics. As such, future long-term research on quantum technologies will likely focus on developing new software languages that could be used for quantum computing, standardisation, building stable and scalable hardware to facilitate commercialisation, eliminating noise and errors, and addressing the challenges of quantum decoherence caused by environmental factors.[175]

B.3.3. Impact on space capability and possible use cases

Widespread application of quantum technologies in the space sector indicates that developments in the field will be crucial in the space domain out to 2040. Current applications of quantum technologies in space include remote sensing for Earth observation and for spacecraft navigation, secure communication through quantum key distribution, quantum computing for simulations and calculations, for instance, on spacecraft movements and trajectories, as well as for data analysis of images and measurements.[176]

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[174] QKD is a form of quantum communication that transmits an encryption key between two parties using photons through the open air, satellites, and fibre optic cables. Source: Parker (2021).

[175] Tarraf (2023); Banafa (2023).

[176] Hughes-Castleberry (2021); The Quantum Leap (2022).

Examples of potential impacts on capability development across the upstream and downstream include:

Upstream:

- Quantum communication could enable new space-based communications channels to be secured through physical properties, rather than simple encryption that can be hacked.[177] Quantum cryptography can enhance security against adversaries using quantum communication technology, and QKD could enable secure inter-satellite and long-distance satellite-to-ground optical communications.
- Quantum technologies have the potential to improve the accuracy of spacecraft navigation and communication, as well as the detection and characterisation of gravitational waves.
- Quantum technologies could support future efforts of space debris removal.[178]

Downstream:

- Developments in quantum technologies have the potential to improve Earth observation capabilities, ranging from seismic activity monitoring and analysis; atmospheric gas monitoring; water quality monitoring; wildfire monitoring; landslide detection; and air pollution analysis.
- Space-based magnetometry may have military and defence applications, such as submarine detection.[179] Future quantum radiofrequency sensing could lead to improvements in intelligence, surveillance and reconnaissance and electronic warfare.[180] Quantum imaging, which detects targets at range and mainly uses the particle nature of light, can have potential military applications in PNT, especially in GPS-denied environments.[181]
- Quantum sensing can contribute to Earth observation and help mitigate the challenges of climate change and environmental events.[182]

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[177] ESA (2023).

[178] Short (2023).

[179] Krelina (2023).

[180] Krelina (2023).

[181] Silberglitt, et al. (2022).

[182] Short (2023).

B.3.4. Considerations for future space regulation

Advances in quantum technologies could prompt regulators to consider some of the following issues:

- Mitigating safety risks associated with reliance on quantum computing and sensing, agnostic of the space domain.
- Minimising risk of error in critical missions or tasks using quantum computing.
- Establishing rules around data governance when relying on quantum technologies for data collection and analysis.
- Clarifying liability and insurance for errors considering that quantum technologies are still in their early stages of development and are vulnerable to environmental factors and radiation as well as to cyber-attacks.
- Ensuring standards and interoperability.

B.4. Critical Technology 4: Engineering biology

Engineering biology applies engineering principles to biology, enabling the manufacture of novel biological systems, such as cells or proteins, which can be applied across a wide range of sectors, including food, materials and health.[183] Bioengineering has the potential to revolutionise space exploration by enabling the development of new technologies and applications, from new materials for spacecraft, to supporting human life in space.

B.4.1. Near-term technology trends

Bibliometric analysis and a literature scan highlight current focus areas for scientific research, including:

- **Synthetic biology**
- **Metabolic engineering**
- **Genome engineering**
- **Tissue engineering**
- **Systems biology**
- **Nanoengineering**
- **Neural inference**
- **Biosensors**.

The bibliometric analysis indicated that engineering biology remains a low priority area of research in relation to space, with only 350 publications identified out of 122,100 publications on space-related S&T. Potential applications of engineering biology to space include:

- Space microbiome
- Plant growth
- Cell regeneration
- Material synthesis
- Cardiac pressure
- Muscle atrophy
- Bone strength
- Temperature observations.

Engineering biology remains an important field as activities in space advance with further crewed missions, as well as with aims to settle on the Moon and Mars. While this field remains under-researched to-date, there is likely to be an uptake in R&D to explore the application of engineering biology to space exploration.

B.4.2. Impact on space capability and possible use cases

Synthetic biology combines principles from biology, engineering and computer science to create new biological systems with specific functions by designing and constructing novel biological parts, devices, and systems. It also involves genetically altering microorganisms for contaminant deterioration or biological

[183] Council for Science and Technology (2023).

targeting, potentially revolutionising biosensing.[184] Metabolic engineering involves modifying metabolic pathways in living organisms to produce desired compounds or improve cellular function, presenting an opportunity for improved fuels and allowing more sustainable space transportation. Advancements in DNA synthesis, sequencing and computational power are key enablers to genome engineering.[185] These approaches could help improve health services.

Examples of potential impacts on space capability across the upstream and downstream include:

Upstream:

- Engineering biology could contribute to the development of lightweight and durable materials which could be used in space suits, spacecraft and future habitats.
- There is also the potential for engineering biology to enable closed-loop life support systems to sustain astronauts in space through water recovery and the production of oxygen. Increased supportability could minimise logistic resupply requirements from Earth.
- Further, engineering biology processes could allow crews to produce food and materials. For example, NASA is developing a technology that can convert carbon dioxide and water into organic compounds to enable microbial biomanufacturing of food products, vitamins, plastics and medicine.[186]
- Advances in engineering biology could contribute to the production of biofuels through the treatment of wastewater, which could enable self-sufficient energy production for spacecraft, allowing for longer transit times for crewed missions.
- Engineering biology has the potential to ensure the health of astronauts during long voyages, by addressing challenges associated with dental health, tissue engineering and emergency wound closure. Wearable biosensors and the ability to regrow tissue could prove critical in enabling crewed missions to Mars and beyond.
- Human augmentation could allow humans to endure a wider range of environments and prevent illness under adverse conditions, potentially enabling longer voyages through space.

Downstream:

- Bio-inspired sensors and imaging systems could be used to provide high-resolution and cost-effective images of the space environment and Earth, which could have application for a range of industries reliant on image analysis, such as agriculture, environmental monitoring and national security.
- There is also potential for new pharmaceutical drugs to be developed and tested in space, making use of the microgravity environment to experiment medicines under conditions not possible on

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[184] Parks, et al. (2017).

[185] Smith (2019).

[186] NASA (2018)

Earth. The ISS is currently hosting tests of HIV/AIDs drugs, with potential for further such experiments to take place.[187]

B.4.3. Considerations for future space regulation

In considering the potential futures of engineering biology, regulators may need to consider some of the following issues:

- Mitigating safety risks associated with the use of novel materials and resources developed through engineering biology.
- Ensuring the safety of closed-loop life support systems and common standards of water treatment, oxygen development and waste management in space.
- Addressing the ethical, legal and liability implications of drug experimentation and ensuring that the effects on Earth and in space remain analogous.
- Ensuring the standardisation and interoperability of biofuels.
- Addressing the ethical and liability concerns of human augmentation for space travel.
- Avoiding the intrusion of biological agents through small-scale targeted attacks on genome engineering projects.[188]

[187] Varda (2023).

[188] Cabinet Office (2023).

B.5. Critical Technology 5: Semiconductors

Semiconductors play a crucial role in the design and manufacture of electronic components for satellites, including microprocessors, memory chips and power amplifiers. These components are essential for the operation of satellites and other space-related digital technology, including for various applications such as communication, navigation and remote sensing.

B.5.1. Near-term technology trends

Bibliometric analysis and a literature scan highlight current focus areas for scientific research, including:

- Digital Integrated Circuits (ICs)
- Analog ICs
- Mixed-signal ICs
- Light-emitting diodes (LEDs) (Optoelectronics)
- Photovoltaic cells (Optoelectronics)
- Optical sensors (Optoelectronics).

The UK Government recognises the importance of semiconductors as a critical emerging technology, due to their use in computing, appliances, communication, transportation, and a range of other applications. The scarcity of semiconductors in recent years due to supply chain disruptions during the COVID-19 pandemic led to upheaval across various industries. Global reliance on semiconductor imports from China has also led to governments re-examining their supply chains and strategies, with the United States introducing export controls in 2022 to limit China's ability to purchase and manufacture semiconductors used in military applications.[189] In 2023, the UK released the National semiconductor strategy, which seeks to strengthen resilience in semiconductor supply chains and leverage the UK's strengths in semiconductor R&D.[190]

Semiconductors remain a key area of space-related research, due to their proliferation across all space assets and ground systems. The bibliometric analysis identified 8,600 relevant sources out of 122,100 publications on space-related S&T. Key areas of intersection include:

- Space launch systems
- Image capture
- Transmission of data, images and video between spacecraft and ground stations
- Spacecraft control
- Global Navigation Satellite Systems (GNSS)
- Optical communication
- Data processing and analysis
- Solar power generation
- Planetary probes and rovers.

[189] Bureau of Industry and Security (2022).

[190] Department for Science, Innovation and Technology (2023).

B.5.2. Possible developments to 2040

Horizon scanning suggests a range of possible areas for future development, including:

- In-space manufacture of semiconductors
- Deep space exploration and imagery
- Space-based solar farms
- Space-based networks and interplanetary internet.

Semiconductors are likely to remain a key focus of R&D, with efforts underway to improve chip design and strengthen global supply chains. As a cross-cutting technology with application across all industries, the space sector will most likely continue to benefit from advances in semiconductor technologies in other fields.

B.5.3. Impact on space capability and possible use cases

Digital integrated circuit (IC) are composed of multiple interconnected transistors (e.g. logic gates, flip flops etc.) on a single semiconductor to process discrete binary signals.[191] Digital ICs have made it possible to transmit data, images and video between spacecraft and ground stations, determine spacecraft position and orientation, capture images of celestial bodies, control spacecraft attitude and propulsion, and analyse data collected by spacecraft, through digital signals. Digital signals are often preferred due to their ability to be transmitted over long distances without degradation (i.e. more radiation tolerant), making digital ICs fundamental to deep space missions. However, they consume more power and are more complex, which can make them more prone to failure in space environments.[192]

Analogue integrated circuits employ analogue components such as resistors, capacitors and transistors on a single semiconductor substrate. Unlike digital integrated circuits, which operate using discrete values of 0 and 1, analogue integrated circuits function using continuous electrical signals that vary in amplitude and frequency.[193] Analogue ICs have made it possible to transmit data, images and video between spacecraft and ground stations, determine spacecraft position and orientation, capture images of celestial bodies, control spacecraft attitude and propulsion, and analyse data collected by spacecraft, through analogue signals. Analogue ICs are capable of providing high precision and accuracy in measurements, consume less power, and are not prone to failure, or hacking and cyber-attacks. However, they are more sensitive to radiation and have limited functionality.[194]

Mixed-signal integration combines analogue and digital circuitry on a single semiconductor die, resulting in highly-integrated functionality in both digital and analogue devices.[195] This particular type enables higher flexibility of environment given its variety in technological methods.

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[191] Avaq (2023).

[192] Barbashov & Trushkin (2016).

[193] Avaq (2023).

[194] Zewe (2022).

[195] IEEE (2023).

Potential impacts on space capability development can be divided into upstream and downstream uses:

Upstream

- Advances in semiconductor technologies are likely to have significant impacts on space hardware, allowing for miniaturisation and improved performance, making space assets lighter, cheaper and more powerful.
- The ability of spacecraft to communicate over longer distances without deterioration due to radiation and other challenges of the space environment could enable crewed and uncrewed missions to the Moon and Mars. Improved communication through advancements in semiconductor technology also contributes to humanity's ability to sustain space habitats over the longer term.
- Smaller and more powerful semiconductors could enable advanced solar photovoltaic cells, improving the solar sails of satellites and allowing them to travel further distances. Advanced semiconductors could allow for the creation of space solar farms to harness the sun's energy above the atmosphere and transmit this power back to Earth.
- Semiconductors could contribute to improved sensing technologies, enhancing our understanding of celestial bodies and increasing space situational awareness. Advances in semiconductor technologies could improve the accuracy and range of space probes and rovers, enabling deeper exploration of our solar system and neighbouring planets and asteroids.

Downstream

- Semiconductors have the potential to improve the speed and accuracy of data transmission and analysis, allowing higher volumes of data to be processed between spacecraft or with ground stations. As such, semiconductors may contribute to improved GNSS and positioning, navigation and timing (PNT), and could have considerable spillover effects across sectors such as transport, logistics, communication and national security.
- As an enabler of other critical technologies such as Quantum and AI/ML, advances in semiconductor technology could empower rapid processing of data, with the potential to advance developments in autonomous technologies, robotics and other areas.

B.5.4. Considerations for future space regulation

UK regulators will need to consider the implications of advancements in this technology area, including:

- Mitigating security risks associated with global semiconductor supply chains and integrated backdoor threats introduced by adversarial elements in the supply network.
- Addressing issues relating to standardisation and interoperability in relation to semiconductors and components used in spacecraft.
- Addressing the resource shortages of raw materials used in semiconductor manufacture and ensuring their ethical sourcing.
- Ensuring a competitive semiconductor market, balanced against the monopolisation of the market by major players.
- Addressing issues relating to Intellectual Property.

B.6. Critical Technology 6: Energy and propulsion

Energy and propulsion are essential enabler for space activities. Advancements in these fields could make it possible to create faster, more efficient and more sustainable space travel. It could also enable permanent settlement of celestial bodies and lead to the realisation of new paradigms of the space economy, such as in-orbit manufacturing. Related fields are those that have to do with natural resource exploration and exploitation, mining, critical minerals, and advanced materials.

B.6.1. Near-term technology trends

Bibliometric analysis and a literature scan highlight current focus areas for scientific research, including:

- Electric/electromagnetic propulsion
- Nuclear power
- Solar propulsion
- Biofuels
- Battery technologies
- Hybrid power.

Though not one of the five critical technologies identified in the Government's S&T Framework, energy and propulsion represents an important element of space-related S&T. Of the 122,100 scientific publications identified through bibliometric analysis, 2,517 relate to energy and propulsion in space. Areas of intersection include:

- Solar energy modelling
- Solar sail propulsion
- Chemical propulsion
- Nuclear thermal propulsion
- Chemical propulsion
- Cryogenic propellants.

B.6.2. Possible developments to 2040

Horizon scanning suggests a range of possible areas for future development, including:

- Geothermal energy exploitation on celestial bodies with volcanic activity.
- Space nuclear propulsion technologies.
- Space-based solar power.
- Radioactive material mining on celestial bodies.
- Nuclear microreactors to support permanent settlement on celestial bodies.
- Solar farms on celestial bodies.
- Methane production from Martian atmospheric CO_2 and hydrogen using Sabatier reaction.
- Hydrogen production through electrolysis of water ice resources on icy bodies.
- AI-enabled materials discovery for space-optimised batteries.

Due to the climate emergency, the world faces an urgent need to decarbonise the energy system. This has led to a significant policy drive to improve energy technologies. Many of these advances in general energy technologies can be adapted for use in space contexts. For example, recent advances in renewable energy technology - particularly in solar, hydrogen, and battery technology - can be tailored to space applications. Much of the nuclear-related technology can be sourced and adapted from the defence sector. AI-enabled materials discovery can lead to improvements in energy-related applications that are particularly suitable for space (e.g., batteries with very high reliability or batteries that are optimised to work in zero gravity).[196]

B.6.3. Impact on space capability and possible use cases

Harnessing energy in efficient ways is a key part of the exploration and exploitation of space, and advances in energy technology can therefore impact space capabilities in a variety of ways. It may become possible to source energy from space. For example, space-based solar power could us orbital power stations that collect solar energy and beam it back to a receiver station on Earth.[197] Additionally, in-situ resource use makes it possible to source energy close to where we want to apply it. For example, methane can be produced from the Martian atmosphere to sustain a permanent base on Mars.[198] Advances in battery technologies could help sustain spacecraft in hostile environments with a lack of readily available energy. For example, they could help sustain landers that only receive a couple of hours of sunlight a day or sustain spacecraft in deep space.[199] Nuclear microreactors could help sustain long-term settlements on celestial bodies. They could provide baseload power independent of the elements and with relatively little amounts of fuel.[200]

Changes in propulsion could enable spacecraft to travel further, at higher speeds, or with more equipment than before. They could also lead to changes in rocket and spacecraft design. Currently, fuel constitutes a large part of the mass and volume of rockets. The result is that many rockets are designed around their fuel system. A smaller and lighter propulsion system could give rise to new forms of design that may be better suited to specific applications.

Examples of potential impacts on space capability development across the upstream and downstream include:

Upstream:

- Improved propulsion technologies can make spacecraft more energy efficient. This can enable faster and longer space missions.
- Currently, spacecraft are designed primarily in function of their fuel system. For example, rockets need to carry very large fuel storage tanks. Implementing different propulsion systems could reduce the design constraints imposed on spacecraft.
- Sustainable energy sources can reduce the environmental impact of space travel.

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[196] Pathak, et al. (2023).

[197] Caton (2015).

[198] Starr & Muscatello (2020).

[199] Krause, et al. (2018).

[200] Gibson, et al. (2017).

- The in-situ exploitation of energy sources could be a fundamental enabler for the construction of long-term bases.

Downstream:

- Data provided by space assets can help improve the efficiency of terrestrial energy systems, for example by aiding the forecasting of wind speeds and solar irradiance.

While new energy and propulsion technologies can offer great benefits, some applications are not without risks. Any nuclear-related applications, for example, could increase the potential impact of accidents involving space assets,[201] and they could increase proliferation risks. In-situ resource utilisation may lead to conflict for resources.[202] Finally, space-based solar power infrastructure may be very large and lead to conflict for optimal locations in various orbits around Earth.

B.6.4. Considerations for future space regulation

While the focus of UK space regulation policy is on regulating capabilities, uses cases and markets, rather than individual technologies, specific regulatory considerations arising from advances in this area include:

- Addressing nuclear non-proliferation risks associated with the deployment of nuclear systems in space.
- Clarifying air traffic safety rules for high-energy beams generated through space-based solar power.
- Clarifying liability and insurance rules for nuclear incidents in space.
- Developing the legal regime for claims made by companies and nation states on natural resources on celestial bodies (including ownership rights and legal enforcement).
- Clarifying norms of responsible behaviour for energy-related dual-use capabilities (e.g., high-energy beams generated through space-based solar power or orbital nuclear installations that can be turned strategically de-orbited to serve as a weapon) to avoid misinterpretation and accidental escalation.
- Developing safe decommissioning practices for nuclear-powered or nuclear-enabled spacecraft.
- Developing health and safety and environmental protection standards for mining, refining, and processing of materials on other celestial bodies.
- Clarifying the status under international humanitarian law of in-orbit power plants (e.g., are they a legitimate target in case of conflict).
- Ensuring standards and interoperability for the use of energy infrastructure in space.

[201] Camp, et al. (2019).

[202] Dapremont (2021).

B.7. Critical Technology 7: Novel materials and manufacturing

Novel materials and manufacturing can transform the space sector by enabling the development of lightweight, high-strength spacecraft and satellite components. They can also improve solar panel performance, thermal control systems and radiation shielding, while reducing mission costs through reusable spacecraft and reduced maintenance.

B.7.1. Near-term technology trends

Bibliometric analysis and a literature scan highlight current focus areas for scientific research, including:

- Lightweight materials
- Self-healing materials
- Biology-based materials
- Additive manufacturing
- Radiation-resistant materials
- Thermal control materials
- Nanomaterials
- Shape-memory materials
- Energy absorbent materials
- Smart textiles
- Regenerative materials.

Though not one of the five critical technologies identified in the Government's S&T Framework, novel materials and manufacturing features in the academic literature on space, with 3,700 sources identified from the bibliometric analysis of 122,100 publications on space-related S&T. Key areas of intersection include:

- Additive manufacturing for spacecraft development
- Antenna design
- Heat shielding and thermal control
- Radiation shielding
- Ultralight fibre-reinforced composites
- Wooden spacecraft.

B.7.2. Possible developments to 2040

Horizon scanning suggests a range of possible areas for future development, including:

- Self-healing materials for satellite maintenance and repairs
- Plasma sensors and solar arrays integrated directly within materials
- In-space additive manufacturing using local resources such as regolith.

Novel materials and manufacturing is likely to receive significant investment from across industry, including outside the space sector, due to applicability to construction, agriculture, transport and other industries. Additive manufacturing could become increasingly reliable as methods and materials are tested in different environments and conditions.

B.7.3. Impact on space capability and possible use cases

Novel materials and manufacturing is already being implemented throughout the space sector. A key driver to this is the reduction of launch costs, which currently cost $10,000-$20,000 (£7,950-£15,900) per kilo, with efforts underway to further reduce costs through the introduction of lightweight materials.[203] Materials used in space are also vulnerable to orbital debris as well as damage by the harsh space environment, which may lead to asset damage or failure. Over the past few decades, the use of fibre-reinforced composites has steadily risen due to their exceptional combination of toughness, low density, high stiffness and strength.[204] Further, there is an ongoing push to improve sustainable usage of space. The use of bio-based materials in space assets, such as satellites and infrastructure to enable human habitation could promote sustainability and reduce the risks of damage by orbital debris. In the vacuum of space, wood is not susceptible to burning or rotting, though it may incinerate on re-entry to Earth's atmosphere. Moreover, bio-based materials do not contribute to light pollution to the extent as shiny metals, and may not pose as high a risk to spacecraft as other types of orbital debris.[205]

Additive manufacturing technology can be applied to conventional materials such as plastics and metals, allowing complex components to be expediently designed, manufactured and tested in-house. Additive manufacturing enables rapid prototyping and reduced production times and costs.[206] Systems generated via this method may require fewer parts, with the ability to print a single piece, rather than the multiple welds required in traditional manufacturing.[207]

Examples of potential impacts on space capability development include:

- Additive manufacturing is likely to have a significant impact on the space sector, due to the reduced cost and complexity of spacecraft components.
- There is currently research underway to test the use of lunar or Mars regolith, as a material source for additive manufacturing, with the potential to enable in-space manufacturing, thereby reducing the energy required to move large quantities of materials into space for on-site construction of habitats and launch infrastructure.[208]
- Lighter and more resilient materials could further reduce costs and improve the lifespan of space technologies, enabling reuse of launchers and components, while facilitating deep-space missions.

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[203] Roberts (2022).

[204] FACC (2023).

[205] Tuner (2023).

[206] NASA (2015).

[207] NASA (2015).

[208] NASA (2015).

- The ability for materials to self-heal could have significant implications for the space capabilities, where assets may not be accessible for in-orbit maintenance or repair by humans.
- The use of bio-based materials such as wood is being tested to improve sustainability and leverage the cheap and lightweight properties of the material. For example, LignoSat, a joint NASA and Japan Aerospace Exploration Agency (JAXA) project, seeks to launch the first wooden satellite into orbit in 2024.

B.7.4. Considerations for future space regulation

While the focus of UK space regulation policy is on regulating capabilities, uses cases and markets, rather than individual technologies, specific regulatory considerations arising from advances in this area include:

- Mitigating safety risks associated with the use of additive manufacturing to design and build spacecraft.
- Addressing issues relating to intellectual property with regard to design and development of spacecraft and components through additive manufacturing.
- Ensuring the safety of novel materials, such as self-healing and bio-based materials, particularly in the use of crewed spacecraft.
- Mitigating the risks of damage to the space environment with use of novel materials and manufacturing.
- Addressing concerns relating to licensing and authorisation with regard to novel materials and manufacturing.
- Ensuring standards and interoperability.

Annex C. Examples of Future Space Capabilities

The space capabilities discussed in Chapter 3 and 4 of this report are captured in the table below, which provides a non-exhaustive list of emerging markets, capabilities, and technologies, explaining how these may take shape, the expected time to uptake, as well as regulatory considerations. This sort of framework can provide a typology to help regulators make sense of emerging technologies and their implications.

Market type	Market	Capability type	Capability	Example technologies	Example use cases	Epoch	Regulatory considerations
Upstream	Manufacturing	Enhanced existing capability	Spacecraft design	AI, Autonomy Robotics Semiconductors Materials and manufacturing	Enables processing of higher volume of data in laying out necessary plans for more efficient and optimised spacecraft design.	5-10 years	Licensing and authorisation
	Space manufacturing	Enhanced existing capability	Reduced costs of manufacturing for space activities	Bio-based materials Semiconductors Additive manufacturing	Use of highly-accessible renewable materials.	5-10 years	Safety
	In-space manufacturing	Novel capability	On-orbit and planetary assembly, and additive manufacturing	Robotics The Internet of Industrial Things Additive manufacturing	Enables efficient connectivity and resilience of systems by conducting ad hoc complex in-space manufacturing operations.	5-10 years	Licensing and authorisation
	Space launches	Novel capability	Improved fuel	Metabolic engineering	Improves the sustainability of space transportation through new drop-in fuels and blends.	Ongoing	Environmental Insurance and responsibility Intellectual property
	Space launches	Novel capability	Flexible space missions	Nuclear propulsion	Improves the ability for back-and-forth traffic of spacecraft due to the efficiency and cost of propulsion.	15-20 years	Environmental Safety

Market type	Market	Capability type	Capability	Example technologies	Example use cases	Epoch	Regulatory considerations
Upstream	Space launches	Novel capability	Interstellar uncrewed space travel	Electric propulsion	Enables fuel-efficient spacecraft to explore deep space as these types of missions do not require swift manoeuvres, while maintaining communication over long distances.	50-60 years	Environmental Safety
	Space launches	Enhanced existing capability	Reduced costs of space operations	Solar propulsion	Launch with less propellant compared to tradition launch propulsion systems.	5-10 years	Environmental Safety
	Space launches	Novel capability	Automated launch and return of space assets	AI	Automation of the processes related to remote launch and return.	5-10 years	Environmental Insurance and responsibility Licensing and authorisation
	Space operations	Novel capability	In-space vehicle maintenance	Self-healing materials	Enables the damaged parts of space assets to be repaired and part of a resilient cycle, allowing spacecraft to maintain trajectory and stability in operations.	15-20 years	Insurance and responsibility Licensing and authorisation
	Space operations	Novel capability	Greener space services	Biology-based materials and new propulsion techniques	Design of space assets with renewable and sustainable materials, as well as low-emission launches and navigation.	Ongoing	Insurance and responsibility Licensing and authorisation Safety

Market type	Market	Capability type	Capability	Example technologies	Example use cases	Epoch	Regulatory considerations
Upstream	Space operations	Novel capability	Improved space predictive services (i.e. early detection of problems)	AI	Analysis of a large volume of data for more accurate forward-looking behaviours anticipated to take place in a wide range of space operations.	5-10 years	Insurance and responsibility Licensing and authorisation Safety Liability
	Space operations	Novel capability	Space traffic management	5G and the Internet of Things	Could enable deployment of signals and emergency beacons for distressed space assets.	5-10 years	Insurance and responsibility Licensing and authorisation Standardisation
	Space operations	Enhanced existing capability	Automated engine operations	Neural inference	Enables detection of anomalies in spacecraft systems based on the behaviour of human crews.	5-10 years	Insurance and responsibility Licensing and authorisation Safety Liability
	Space operations	Enhanced existing capability	Automated navigation	AI	Enables automation and potential autonomy of navigation process.	5-10 years	Insurance and responsibility Licensing and authorisation Safety Liability
	Space operations	Enhanced existing capability	Improved and precision-focused orbital manoeuvring	Chemical propulsion and quantum metrology	Higher accuracy of PNT due to improved propulsion and quantum technologies.	5-10 years	Environmental Safety

Market type	Market	Capability type	Capability	Example technologies	Example use cases	Epoch	Regulatory considerations
Upstream	Space operations	Enhanced existing capability	Greater autonomy of space services	AI Autonomy Robotics	Efficient automation of dangerous, time-consuming or costly activities, such as in-orbit repairs.	5-10 years	Insurance and responsibility Licensing and authorisation Safety Liability
	Space operations	Enhanced existing capability	Increased space network resilience	Novel materials and 5G networks	Higher connectivity and adaptability between space assets, physically protected by materials' self-healing characteristics.	5-10 years	Standardisation
	Space operations	Enhanced existing capability	Protecting dark and quiet skies	Biology-based materials	Creation of space assets that reduce light and environmental pollution in various orbits.	5-10 years	Safety
	Orbital servicing	Novel capability	Automated docking	AI Autonomy Robotics	Enables automation and potential autonomy of docking process, informed decision-making and anomaly detection to enhance safety during docking.	5-10 years	Safety Insurance and responsibility Standardisation Licensing and authorisation
	Space tourism and exploration	Novel capability	Interplanetary crewed space travel	Nuclear propulsion and digital integrated circuits	Enables energy-efficient spacecraft in the vicinity of planets in our solar system (e.g. Mars) and ensures communication over long distances.	15-20 years	Environmental Safety

Market type	Market	Capability type	Capability	Example technologies	Example use cases	Epoch	Regulatory considerations
Upstream	Human safety and survival in space	Novel capability	Improved space suits and general space accessories	Synthetic biology Materials	Enables more complex, safer, long-term and long-distance crewed space missions, whilst also increasing the possibility of human settlement in space.	15-20 years	Safety
	Human safety and survival in space	Novel capability	Biological safety of living beings in space and extraterrestrial environments	Synthetic biology	Enables biological targeting and contaminant deterioration, revolutionised biosensing through altered microorganisms.	15-20 years	Environmental Safety
	Human safety and survival in space	Novel capability	Extended crewed space roaming	Genome engineering and biosensors	Enables creation of living beings, or alteration of current ones, more resistant to interplanetary and deep space travel, as well as space activities on any regolith.	50-60 years	Intellectual property Ethics
	Human safety and survival in space	Novel capability	Extraterrestrial food system	Genome engineering and biosensors	Enables safe and diverse creation of edible products in extraterrestrial conditions through genomic alteration of existing terrestrial crops and plants at different stages of growth.	15-20 years	Intellectual property Ethics

Market type	Market	Capability type	Capability	Example technologies	Example use cases	Epoch	Regulatory considerations
Upstream	Human safety and survival in space	Novel capability	Extraterrestrial habitat	Nuclear power and biology-based material	Enables development of a base made of durable, resistant materials and sustainable functioning thanks to nuclear power sources.	15-20 years	Environmental Safety
	Human safety and survival in space	Novel capability	In-space food production	Genome engineering	Enables growth of plants and other edible products during space travel.	5-10 years	Intellectual property Ethics
	Human safety and survival in space	Novel capability	Physical safety of space assets	Quantum metrology and communication	Allows detection and characterisation of in-space gravitational waves, in addition to timekeeping, geolocation, and geodesy, allowing adequate itinerary recalculation as a result, while communicating effectively with terrestrial bases.	5-10 years	Standardisation Safety
	Human safety and survival in space	Novel capability	Radiation shielding and thermal control of spacecrafts	Materials	Enables spacecraft protection from space threats and travel sustainable living conditions.	10-15 years	Safety
	Human safety and survival in space	Novel capability	In-space drugs manufacturing	AI Robotics Synthetic biology	Enables testing and development of drugs in environments without gravity or other harsh extraterrestrial environments, allowing expansion of physical properties of medicine.	Ongoing	Safety

Market type	Market	Capability type	Capability	Example technologies	Example use cases	Epoch	Regulatory considerations
Upstream	Human safety and survival in space	Novel capability	Space-based health services	AI Nano engineering	Enables use of silicon nanomaterials for delicate medical interventions or detection of infected cells as a result of dangerous exposure to in-space threats, opening doors for more complex crewed missions.	5-10 years	Safety Intellectual property
	Human safety and survival in space	Novel capability	Space-based health services	Neural inference and biosensors	Enables detection of anomalies in human health system during space missions.	Ongoing	Safety Intellectual property
	Human safety and survival in space	Novel capability	Space-based health services	Tissue engineering	Enables in-space 3D bioprinting of organs and skin tissue generation for all-encompassing medical assistance, towards enabling more complex crewed missions.	10-15 years	Safety Intellectual property
	Human safety and survival in space	Enhanced existing capability	Increased knowledge of the limits of human biology	Engineering biology	Design of wearable devices to assess human health systems in various in-space environments and detect challenging conditions.	Ongoing	Intellectual property
	Space debris removal	Novel capability	Improved processes of space assets disposal	AI	Automation of the processes related to remote disposal of space assets.	5-10 years	Environmental Insurance and responsibility

Market type	Market	Capability type	Capability	Example technologies	Example use cases	Epoch	Regulatory considerations
Upstream	Space debris removal	Novel capability	Improved processes of space assets recycling	AI and novel materials	Automation of the processes related to remote recycling of sustainable and recyclable materials, especially by separating and filtering the components of a space asset efficiently. Remote re-operation of space assets for reuse of sustainable and adaptable materials.	10-15 years	Environmental Insurance and responsibility
	Across all markets	Enhanced existing capability	Reduced space engines malfunctions	AI	Detection of malfunctions before they occur through the high-speed processing of high volumes of data.	5-10 years	Insurance and responsibility Licensing and authorisation Safety Liability
Downstream	Space-based communications	Enhanced existing capability	Physical encryption of long-distance satellite-to-ground communications	Quantum cryptography	Enhances volume of data transfers from space to Earth and vice versa, and enables sensitive data to be transferred to and from off-planet data centres.	5-10 years	Standardisation Liability
	Space-based communications	Enhanced existing capability	Physical encryption of inter-satellite communications	Quantum cryptography	Enhances volume of in-space data transfers and enables sensitive operations on-orbit	5-10 years	Standardisation Liability

Market type	Market	Capability type	Capability	Example technologies	Example use cases	Epoch	Regulatory considerations
Downstream	Space-based communications	Enhanced existing capability	Increased scale of digitalisation of space services	5G/6G+ networks	Higher connectivity for satellites constellations and spacecrafts.	Ongoing	Standardisation
	Space-based communications	Enhanced existing capability	Expanded domain coverage of communications	Digital integrated circuits	Signals can travel over long distances without deterioration because they are more radiation tolerant.	5-10 years	Standardisation
	Space-based communications	Enhanced existing capability	Improved flexible satellites	Quantum computing	Higher connectivity and responsiveness of the satellite once it is launched allowing the space asset to multitask through all domains of activity.	5-10 years	Insurance and responsibility Licensing and authorisation
	Space-based communications	Enhanced existing capability	Satellite backhaul	5G/6G+ networks	Enables higher connectivity for uniform terrestrial digitalisation and access to global coverage thanks to satellite constellations having a higher-speed backhaul.	Ongoing	Standardisation
	Space communications	Novel capability	Reduced latency of communications	5G/6G+ networks and the Internet of Things	High connectivity for enhanced vertical and horizontal communications that transit through space.	Ongoing	Standardisation

Market type	Market	Capability type	Capability	Example technologies	Example use cases	Epoch	Regulatory considerations
Downstream	Space-based communications	Novel capability	Frequency transfer	Quantum communication	Enables adequate computing power for analysis of frequencies and opens up transfer corridors.	5-10 years	Standardisation Liability
	Space-based communications	Enhanced existing capability	Improved spectrum management processes	5G/6G+ networks	Higher coverage of the electromagnetic spectrum for more targeted uses, enabling the possibility for more specific regulations.	5-10 years	Standardisation
	Space-based weather forecasting	Enhanced existing capability	Improved meteorological predictions	Quantum computing	More accurate weather forecasts, also allowing an increased time range for wider climate predictions.	5-10 years	Standardisation
	Space-based science	Enhanced existing capability	Understanding of the creation of the universe	Systems biology	Enables processing of cosmic and celestial ecosystems.	Ongoing	Ethics
	Space-based science	Enhanced existing capability	Natural capital valuation	Machine learning and quantum imagery	Creation of space imagery and Earth depiction for a global 'Overview effect' to happen.	5-10 years	Liability Privacy
	Space-based science	Enhanced existing capability	Enhanced accuracy in spatial measurements	Analog integrated circuits	Higher coverage of amplitudes and frequencies for a more precise analysis of any space body (natural and human-made), through multiple output formats.	Ongoing	Environmental Standardisation

Market type	Market	Capability type	Capability	Example technologies	Example use cases	Epoch	Regulatory considerations
Downstream	Space-based science	Enhanced existing capability	In-space based scientific instruments	AI and digital integrated circuits	Enables telescopes, and other scientific instruments, to operate remotely and communicate findings.	5-10 years	Insurance and responsibility Licensing and authorisation Safety Liability
	Space-based defence	Enhanced existing capability	Enhanced national security	Quantum computing	More accurate Intelligence, Surveillance, Reconnaissance (ISR) capabilities in general.	5-10 years	Privacy Liability
	Space-based defence	Enhanced existing capability	Improved location and PNT services	Quantum sensors and quantum communication	More accurate detection of light photons in all space environments while ensuring effective post-finding communication.	5-10 years	Standardisation Liability Privacy
	Space manufacturing	Enhanced existing capability	Reduced manufacturing costs for space objects	AI and digital integrated circuits	Design of chips locally through optimised and cheaper processes.	5-10 years	Licensing and authorisation
	Space-based power	Novel capability	In-space efficient energy production	Novel materials	Enables capture of space-based power in a sustainable and more productive way.	Ongoing	Environmental Safety
Downstream	Across all markets	Enhanced existing capability	Understanding of humanity's role in the cosmos and alien life	All key future capabilities	All-encompassing use of space and limitless exploration of the cosmos.	Ongoing	Ethics

Market type	Market	Capability type	Capability	Example technologies	Example use cases	Epoch	Regulatory considerations
Downstream & upstream	Space-based power	Novel capability	In-space efficient electricity production	Mixed-signal integrated circuits	Enables flexible and low-cost electron emission in space environments.	5-10 years	Environmental Safety Insurance and responsibility
	Space-based communications	Novel capability	In-space communications relay	5G/6G+ and the Internet of Things	Enables higher volumes of information to be transmitted between space assets due to improved connectivity.	5-10 years	Standardisation
	Space-based communications	Novel capability	Off-planet data centres for collection, storage, and processing	5G/6G+ networks and the Internet of Things	Enables higher and quicker global broadband connectivity from in-orbit to ground and longer distances, communications prone to safe and efficient data transfers between terrestrial soil and any orbital belt.	5-10 years	Standardisation
Downstream & upstream	Space mining	Novel capability	Extraterrestrial mining	Genome engineering and machine learning	Enables adaptation of living beings (including microscopic beings) more resistant to space activities on any regolith for resource extraction activities that require human assistance, while leaving parts of the decision-making process or repetitive tasks to artificial intelligence.	50-60 years	Intellectual property Ethics

Market type	Market	Capability type	Capability	Example technologies	Example use cases	Epoch	Regulatory considerations
	Orbital servicing	Novel capability	In-space refuelling	AI Autonomy Robotics Energy tech	Enables automation and optimisation of a refuelling station in space.	10-15 years	Environmental Safety
	Space tourism and exploration	Novel capability	Space tourism	Nuclear propulsion	Enables spacecraft to flexibly transfer back and forth between the cis-lunar belt and terrestrial soil.	15-20 years	Environmental Safety