Emerging threats and opportunities for the UK National Space Strategy

James Black, Linda Slapakova, Kevin Martin
This research was conducted through RAND Europe’s Centre for Futures and Foresight Studies (CFFS). The CFFS brings together deep expertise in futures research methods along with specialist sector knowledge to help our clients plan for the future in conditions of uncertainty.

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Recent years have witnessed major changes in how humans are accessing and use space. Technology and innovation are driving down costs and fuelling a boom in the number of objects launched into space. The Earth’s orbit is becoming increasingly congested, contested and competitive as a result, with government, military and commercial actors all pursuing a wide variety of different space-related activities. Nation-states and private companies alike are also investing in missions further afield, whether to colonise the Moon, explore Mars, push the boundaries of scientific understanding, or exploit the resources of the solar system.

Looking out to 2050, the future direction of the space domain and the already complex dynamics of the space economy is uncertain. Against this backdrop, the UK Government has published a National Space Strategy setting out the UK’s own ambitions, priorities and policy levers for the future. To inform development of the strategy, in June 2020 the UKSA identified a need to establish a more holistic understanding of the changing landscape of space-related activities and identify possible ‘game-changing’ developments that might have a long-term impact. To this end, RAND’s Centre for Futures and Foresight Studies (CFFS) produced a study to understand the breadth, complexity and impact of possible future activities in, through or enabled by space out to 2050.

This CFFS study, Future uses of space out to 2050, presents an extensive breadth of activities and markets that contemporary literature and activity suggest may form part of the space economy out to 2050. These different applications and markets involve a wide range of civil, commercial and military stakeholders all seeking to utilise space-based products and services for a variety of purposes. The overarching results of this analysis are captured in a concise main report. This examines the major drivers of change to 2050 in both the ‘upstream’ and ‘downstream’ segments of the space economy and consider the possible implications for prosperity, the environment, security, science and discovery, and international collaboration.

To further capture the broad scope and nature of possible future space-related activities and markets and the associated risks and opportunities for the UK space sector, the research team has also developed thematic technical annexes to accompany the main report. These cover fifteen sectors, as shown in the figure below.

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2 Though this report is being published following the launch of the UK National Space Strategy, all underpinning research was completed prior to the strategy’s finalisation and release.
3 Black et al. (2021).
4 The upstream segment is understood here to encompass ‘activities related to sending spacecraft and satellites into space, including the manufacturing of launch vehicles and satellites.’ The downstream refers to ‘activities utilising space data to offer products or services (space applications) as well as ground segment applications (space operations).’
Figure 0.1 Topic areas covered by technical annexes to the main report

**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

**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

**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

**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)

**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.)

**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)

Source: RAND Europe analysis.
This document elaborates on the possible future uses of space envisaged for these fifteen sectors. Specifically, it summarises the breadth of possible future applications and use cases in relation to space-based, terrestrial and ‘hybrid’ markets, along with the main actors involved, the value proposition to different end users, and possible timelines, barriers and enablers for realising these ambitions. It concludes by summarising the potential impact and implications in terms of prosperity, the environment, security, science and discovery, and international collaboration. This includes both possible benefits and risks, recognising that developments in space out to 2050 may hold great promise but also come with distinct costs, trade-offs and externalities – some of which may prove highly disruptive to existing markets.

As is further discussed in the main report, this analysis is not intended to provide a firm prediction of what will or should happen in the fast-changing space sector. Instead, it provides a summary of government, military, industry, academic and civil society projections as to what might happen, based on current or anticipated changes in technology, markets and wider society. The analysis is focused on developments in the space economy itself and does not investigate terrestrial alternatives (e.g. the feasibility of developing alternative means of delivering services currently provided by satellites) in the same detail.

The research findings presented in this technical annex are accompanied by a tailored bibliography, with a full bibliography available in the main report to provide additional reading for anyone interested in possible developments at the intersection of the space economy and various sectors, out to 2050.

The Centre for Futures and Foresight Studies works across RAND to deliver multi-disciplinary futures research and policy analysis to help private and public sector institutions understand and think about the future. Ranging from scenario planning to high-level gaming to horizon-scanning, the CFFS produces actionable insights across both near- and longer-term time horizons.

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## Abbreviations

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<tr>
<td>AI</td>
<td>Artificial Intelligence</td>
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<tr>
<td>AMF</td>
<td>Additive Manufacturing Facility</td>
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<td>AR</td>
<td>Augmented Reality</td>
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<td>ASAT</td>
<td>Anti-Satellite</td>
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<tr>
<td>AU</td>
<td>Astronomical Unit</td>
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<tr>
<td>BIM</td>
<td>Building Information Modelling</td>
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<tr>
<td>C4ISTAR</td>
<td>Command, Control, Communications, Computers, Intelligence, Surveillance, Target Acquisition and Reconnaissance</td>
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<tr>
<td>CAGR</td>
<td>Compound Annual Growth Rate</td>
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<tr>
<td>CAV</td>
<td>Connected and Autonomous Vehicle</td>
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<tr>
<td>CBRN</td>
<td>Chemical, Biological, Radiological, Nuclear</td>
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<tr>
<td>CFFS</td>
<td>Centre for Futures and Foresight Studies</td>
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<td>CIIP</td>
<td>Critical Infrastructure Protection</td>
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<tr>
<td>CNI</td>
<td>Critical National Infrastructure</td>
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<tr>
<td>CPGS</td>
<td>Conventional Prompt Global Strike</td>
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<tr>
<td>CPRS</td>
<td>Commercial Polymer Recycling System</td>
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<tr>
<td>CRS</td>
<td>Commercial (Orbital) Re-Supply Services</td>
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<tr>
<td>DARPA</td>
<td>Defense Advanced Research Projects Agency</td>
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<tr>
<td>DSOC</td>
<td>Deep Space Optical Communications</td>
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<tr>
<td>Dstl</td>
<td>Defence Science &amp; Technology Laboratory</td>
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<tr>
<td>DTH</td>
<td>Direct-to-Home</td>
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<tr>
<td>DTIB</td>
<td>Defence Technological and Industrial Base</td>
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<tr>
<td>EASOS</td>
<td>Earth and Sea Observation System</td>
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<td>EM</td>
<td>Electromagnetic</td>
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<td>EO</td>
<td>Earth Observation</td>
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<td>Acronym</td>
<td>Full Form</td>
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<tr>
<td>ESA</td>
<td>European Space Agency</td>
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<td>EU</td>
<td>European Union</td>
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<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
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<tr>
<td>GEO</td>
<td>Geostationary Orbit/Geosynchronous Equatorial Orbit</td>
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<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
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<tr>
<td>GPS</td>
<td>Global Positioning System</td>
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<tr>
<td>GVA</td>
<td>Gross Value Added</td>
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<td>HADR</td>
<td>Humanitarian Air and Disaster Relief</td>
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<tr>
<td>HAPS</td>
<td>High Altitude Pseudo Satellite</td>
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<tr>
<td>HMT</td>
<td>Human-Machine Teaming</td>
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<td>IoT</td>
<td>Internet of Things</td>
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<tr>
<td>IIoT</td>
<td>Industrial Internet of Things</td>
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<tr>
<td>IP</td>
<td>Intellectual Property</td>
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<tr>
<td>IPIN</td>
<td>Indoor Positioning and Navigation</td>
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<td>ISM</td>
<td>In-Space Manufacturing</td>
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<tr>
<td>ISRU</td>
<td>In-Situ Resource Utilisation</td>
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<tr>
<td>ISS</td>
<td>International Space Station</td>
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<tr>
<td>ITU</td>
<td>International Telecommunication Union</td>
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<tr>
<td>JIT</td>
<td>Just in Time</td>
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<tr>
<td>LEO</td>
<td>Low Earth Orbit</td>
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<td>M2M</td>
<td>Machine-to-Machine</td>
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<tr>
<td>MaaS</td>
<td>Mobility as a Service</td>
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<tr>
<td>MACA</td>
<td>Military Assistance to Civil Authorities</td>
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<tr>
<td>METI</td>
<td>Messaging Extra Terrestrial Intelligence</td>
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<tr>
<td>MR</td>
<td>Mixed Reality</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<tr>
<td>NATO</td>
<td>North Atlantic Treaty Organisation</td>
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<tr>
<td>NGO</td>
<td>Non-Governmental Organisation</td>
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<tr>
<td>NEO</td>
<td>Near Earth Objects</td>
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<tr>
<td>OST</td>
<td>Outer Space Treaty</td>
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<tr>
<td>PNT</td>
<td>Precision, Navigation and Timing</td>
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<td>RF</td>
<td>Radio Frequency</td>
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<tr>
<td>SATCOM</td>
<td>Satellite Communications</td>
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<tr>
<td>Acronym</td>
<td>Definition</td>
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<tr>
<td>SAR</td>
<td>Search and Rescue</td>
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<tr>
<td>SETI</td>
<td>Search for Extra Terrestrial Intelligence</td>
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<tr>
<td>SME</td>
<td>Small and Medium Enterprise</td>
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<tr>
<td>SSA/SST</td>
<td>Space Situational Awareness/Space Surveillance and Tracking</td>
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<tr>
<td>STEM</td>
<td>Science, Technology, Engineering and Mathematics</td>
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<tr>
<td>TDRS</td>
<td>Tracking and Data Relay Satellites</td>
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<tr>
<td>THF</td>
<td>Tremendous High Frequency</td>
</tr>
<tr>
<td>UAS</td>
<td>Unmanned Aerial System</td>
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<tr>
<td>UK</td>
<td>United Kingdom of Great Britain and Northern Ireland</td>
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<tr>
<td>UKSA</td>
<td>UK Space Agency</td>
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<td>UN</td>
<td>United Nations</td>
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<td>UNFCCC</td>
<td>United Nations Framework Convention on Climate Change</td>
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<td>USA</td>
<td>United States of America</td>
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<tr>
<td>V2I</td>
<td>Vehicle-to-Infrastructure</td>
</tr>
<tr>
<td>V2V</td>
<td>Vehicle-to-Vehicle</td>
</tr>
<tr>
<td>VR</td>
<td>Virtual Reality</td>
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<tr>
<td>ZBLAN</td>
<td>Zirconium Barium Lanthanum Aluminum Sodium Fluoride</td>
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Annex A. Agriculture

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<tr>
<td><strong>Definition</strong></td>
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<tr>
<td>This cluster comprises all those activities in or enabled by space that are focused on the science and practice of farming, including cultivation of the soil to grow crops or rear animals to provide food, wool, leather, oxygenation, carbon capture, biofuel, and other products.</td>
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**Summary**

The agricultural sector is not only responsible for feeding the world's population, but also comprises an important source of income and a major component of the global economy. Estimates suggest that over a billion people work in agriculture around the world, with approximately one-third of the economically active population deriving their livelihoods through farming or related activities.\(^5\)

Agricultural techniques in leading economies are less labour-intensive and make greater use of mechanisation, bioscience and digital technology, with the sector contributing to national prosperity, jobs, innovation, exports, food security and safety, and environmental management. In 2019, agriculture provided around 1.45% of jobs in the UK, but the agri-food sector accounted for a Gross Value Added (GVA) of £120bn, or 6.3% of national GVA, as well as exports of £23.6bn.\(^6\)

Space-based products and services are already beginning to have a significant and growing effect on the agricultural sector. Out to 2050, the impact of space on agriculture is expected to increase substantially, both in terms of breadth and depth. This includes new developments in space-based food production, hydroponics and closed-loop ecosystems, as well as the use of space-based products and services such as Earth Observation (EO), Satellite Communications (SATCOM) and Precision, Navigation and Timing (PNT) in the terrestrial agriculture sector. For example, space may enable innovations in precision agriculture and the use of remote monitoring, yield and risk modelling, and autonomous and robotic systems to increase agricultural productivity in a range of environments.

Future uses of space for space-based as well as terrestrial agriculture could therefore also have extensive knock-on benefits for environmental sustainability and the growth of the net-zero economy. Furthermore, they could enable future space-based habitats and long-duration space exploration missions through in-situ production of food and other supplies, as well as one day supporting colonisation and terraforming efforts on Mars or other celestial bodies.

While space-based markets may face greater technical and financial barriers given the difficulties and costs associated with production of food in conditions of microgravity and limited space (e.g. on spacecraft or lunar/Martian habitats), the use of space to support terrestrial agriculture may be hindered more by varying levels of awareness among end users concerning costs and benefits of applying novel space-based applications.

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\(^5\) [Globalagriculture.com (2020)].

\(^6\) [UK Government (2020b)].
### Relevant use cases

<table>
<thead>
<tr>
<th>Space markets</th>
<th>Hybrid markets</th>
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| **Orbital food production for space markets**: Space-based farming may provide supplies for long-term space missions and orbital, lunar or Martian settlements, feeding the growing space population without reliance on Earth.\(^7\) Plants may also bring psychological benefits for long-term space missions and colonies.  
**Orbital food production for Earth markets**: Space-based farming may provide enhanced genetic plant engineering or self-contained crop growing systems for Earth markets, initially focused on novelty or high-value items (e.g. space coffee), but expanding the product range over time.\(^8\)  
**Hydroponic gardens**: Hydroponics is a subset of hydroculture, which is a method of growing plants without soil by using mineral nutrient solutions in water.\(^9\) Hydroponic gardens can, similarly to orbital food production using soil, provide supplies for space missions and space habitats.\(^10\)  
**Closed-loop ecosystems/life-support systems**: Closed-loop ecosystems and life-support techniques can use plants and algae to recycle air, water and waste while producing critical supplies such as oxygen, drinking water and food.\(^11\)  |
| **Sustainable intensification**: Satellite technologies can be used to improve sustainable intensification, or processes through which ‘agricultural yields are increased without adverse environmental impact and without the conversion of additional non-agricultural land’.\(^12\)  
**Connectivity for agri-logistics**: SATCOM and PNT can enable ‘applications that help farmers to increase efficiency and to comply with regulations and new standards’, such as through farm machinery monitoring and asset management.\(^13\)  
**Connectivity for agricultural Internet of Things**: SATCOM and PNT services could support Industrial Internet of Things (IIoT) farm management systems, which enable real-time monitoring and coordination of networked sensors, equipment and robotic farming systems.\(^14\)  |

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7 Factories In Space (2020a).  
8 Factories In Space (2020a).  
9 Hughes et al. (2018).  
10 Jucha (2016).  
11 ESA (n.d.d).  
14 Digiteum (2019).
### Terrestrial markets

- **Real-time EO and monitoring for farming**: EO may be used to support farming through improved detection and monitoring of phenomena such as land use, crop productivity or disease, and facilitate farm system management and optimisation.15

- **Precision agriculture**: This includes ‘the application of different technologies and solutions to manage the variability of agricultural production to improve crop yield and reduce environmental impact’, including through farm machinery guidance, automatic steering, variable rate applications, yield, biomass and soil condition, and livestock tracking and virtual fencing to optimise agricultural practices.16

- **Precision natural resources management**: EO could support improved input and farm management, including management of water resources and drought.17

- **Meteorological monitoring for the agricultural sector**: EO data may be used in agro-meteorological measurement and analytics models to estimate and predict key parameters such as crop biomass, health and yield.18

- **Support to regulation, compliance and subsidy controls**: EO could be applied for improved monitoring of regulatory compliance by farmers, as well as adoption of improved regulation and subsidy controls in the agriculture sector.19

### Main actors

There is a wide variety of actors involved in agricultural value chains, with varying levels of exposure to and involvement in applying space technologies in this sector.

Government agencies such as the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) are already actively promoting the benefits of increasing use of space technologies to support farming on Earth, as well as to adapt agricultural techniques to support production of food and other products in space. In the UK, ‘Agriculture’ is one of the designated focus areas of the Satellite Applications Catapult, with special emphasis on promoting space products and services that contribute to more sustainable global supply chains and high value production. This is supported by development of a Digital Agri-Test Centre at Westcott focused on the application of 5G, robotics, Unmanned Autonomous Systems (UAS) and satellite technologies in this sector.

Commercial actors in the development of space-based agriculture markets include Alginity, DoubleTree by Hilton, Zero G Kitchen, CemVita Factory, Aleph Farms with 3D Bioprinting Solutions, and Orbital Farm. Existing food and drink manufacturers have also outlined plans for new product lines originating partially or entirely in space: Budweiser, for example, has announced its ambition to be the first beer on Mars, and has joined with other commercial partners to pursue research into microgravity beer.20

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15 Catapult Satellite Applications (2017a).
16 Catapult Satellite Applications (2017a).
17 Catapult Satellite Applications (2017a).
19 Catapult Satellite Applications (2017a).
20 Factories In Space (2020c).
### Value proposition to end users

| Government (civil) | • Support for monitoring and boosting sectoral productivity.  
|                   | • Support for food safety and security initiatives.  
|                   | • Support for monitoring and enforcing compliance with relevant legislation and regulatory frameworks, including environmental protections and land subsidy controls.  
| Government (military) | • Monitoring of regional food and water security and biosecurity as potential drivers of intra- or inter-state conflict.  
|                      | • Improvements in food production techniques for future sustained military operations in space (or on Earth).  
| Civil (commercial) | • New market opportunities arising from space-based food production and provision of other products and services for the terrestrial agricultural sector.  
|                   | • Year-round orbital crop production given lack of seasons, ensuring controlled environment and predictable yields.  
|                   | • Increased workforce productivity for farms, given increasing use of space-enabled Internet of Things (IoT) solutions and precision agriculture.  
|                   | • Increased yields and sustainable intensification of land use to boost profitability while managing the environmental impact.  
|                   | • Benefits for farmers and agricultural corporations, agricultural commodity traders and agricultural investors through improved monitoring capabilities (e.g. tracking crop yields).  
| Civil (other) | • Advancing scientific research in farming methods and mitigation of the environmental impact of agriculture.  
| Consumers | • Reduced cost and increased choice in food, drink and other products, including new types (e.g. space-grown products).  
|           | • Increased resilience of food supply chains and environment, resulting in reduced likelihood of famine or drought.  
|           | • Improved quality of agricultural products through facilitating compliance with ethical and environmental standards.  

### Estimate of timeframes

EO, SATCOM and PNT services are already being used in various agricultural applications, with government or commercial R&D projects underway to explore more game-changing future possibilities. Some space applications for terrestrial agriculture – such as use of satellite-enabled weather prediction and machinery guidance – are already in the early stages of adoption, while others, such as precision livestock tracking and virtual fencing, are still in early development.\(^{21}\)

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Looking towards space-based production, rates of growth will be dependent in large part on the progress made towards establishing orbital, lunar or Martian settlements in the 2020s, 2030s and 2040s (as a key source of demand for food and other products). Government agencies and commercial actors are already actively exploring potential new markets, products and services. The principles for closed-loop life-support systems have, for example, been tested at the International Space Station (ISS) through a hybrid ‘algae-powered bioreactor’ life support system. In 2020, NASA funded five new projects to improve food and crop production in microgravity. In terms of space-based production of food and other agri-products for Earth markets, the focus is likely to remain on novelty and high-value items (e.g. alcohol, coffee) in the near-term, with the potential for establishing more large-scale operations in the 2030s and 2040s as costs fall and demand grows.

### Drivers and enablers

Agricultural applications are enabled by several upstream markets, including advances in terrestrial manufacturing, robotics, PNT and EO technologies. Additional technological enablers for realising space-based food production include:

- Systems for managing exposure to solar radiation outside of the Earth’s magnetosphere.
- Advanced lighting and sensor technologies to support crop production.
- Advanced water-recovery techniques (particularly for hydroponics).
- Capabilities for producing plant habitats compatible with microgravity conditions.
- Availability and affordability of orbital, lunar or other (e.g. Martian) habitats large enough for crop-plant production.

Current projects and advances in biology and engineering to develop these capabilities include efforts under NASA’s Space Life and Physical Science Research and Applications Division (SLPSRA) and Advanced Exploration Systems (AES). These are focused on advancing approaches to the design, monitoring and management of microgravity root-zones, food and crop production, as well as spatial design of astro-gardens.

Key enablers for space-based use cases in terrestrial agriculture include further advances in EO, SATCOM and PNT technologies, as well as ‘adjacent’ technologies such as computer vision, robotics, autonomy, AI/ML and Big Data analytics. Additional non-technical enablers include access for UK service providers and operators to partnerships with dominant agricultural equipment manufacturers, as well as strong levels of demand for ever-more efficient agricultural techniques given a growing population and concerns about food security, resource management and sustainable intensification.

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22 Mathewson (2019).
23 Factories In Space (2020a).
24 Monje et al. (2003).
26 Factories In Space (2020a).
27 Factories In Space (2020a).
28 NASA (2020b).
Future uses of space out to 2050 - Technical annex

Potential barriers and challenges to implementation

A number of complex technical challenges present enduring barriers to the development of space-based farming techniques, including limitations imposed by ‘high and low extremes in ambient temperatures, reduced atmospheric pressures, atmospheres containing high volatile organic carbon contents, and elevated to super-elevated CO2 concentrations’. Managing closed-loop systems in space requires overcoming highly complex botanical and engineering challenges to ensure that there is no damaging imbalance in any inputs or outputs, and that nutrients, climate conditions and many other variables are optimised in real-time to prevent cascading failures.

The cost of launch and space operations is also an important factor. High costs make the construction of large-scale orbital food production facilities unlikely in the near term. Conversely, if launch costs fall significantly, it may prove cheaper and simpler to supply orbital installations with food launched up from Earth sources rather than establish local agricultural production in space.

Space-based applications for terrestrial markets may face other barriers too, for example related to high upfront costs for smaller agri-tech stakeholders to adapt to certain new technologies. Existing estimates indicate that use of Global Navigation Satellite System (GNSS) applications would be viable ‘for farms above 50 ha’, while ‘globally 84% of farms are smaller than 2 ha, and operate about 12% of the world’s farmland’, though this may change over time as services improve and costs fall. There may also be uncertainties among potential end users concerning the performance of space-enabled agricultural technologies and a lack of clarity concerning the benefits and risks of new technology. The benefits of space-based applications in this area may also be distributed unequally across different countries and regions, creating a growing gap between the farming techniques of poor nations or smaller farm-owners and the capacity of large agri-businesses to implement new space-enabled technologies.

Summary of potential impacts and implications for the space economy

Prosperity
- New commercial markets for space-based and space-enabled agricultural products and services.
- Reduced costs for supplies in space, boosting economic competitiveness and sustainability of other space markets.
- Increased productivity in the agricultural sectors of developed economies, increasing Gross Domestic Product (GDP) growth and exports.
- Increased productivity in the agricultural sectors of developing economies, freeing up labour to move into other industries (e.g. manufacturing, services) and from rural to urban areas.

Environment & net-zero economy
- Monitoring of and reductions in the environmental impact of terrestrial agriculture by enabling sustainable intensification.
- Contribution to resource and water management.
- Increased effectiveness of regulatory and subsidy mechanisms and higher levels of compliance by farmers and businesses.
- Use of advanced agri-technologies to pursue climate change targets, boost biofuels production and monitor biomass (e.g. for purpose of carbon capture and offsets markets).

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31 Monje et al. (2003).
32 Catapult Satellite Applications (2017a).
| National security & defence | • Improved food security and biosecurity.  
• Prevention or mitigation of conflict over natural resources. |
|-----------------------------|------------------------------------------------------------------|
| Science & discovery         | • Feeding and supporting space-based habitats and long-duration space exploration missions.  
• Informing scientific research in microgravity effects and other challenges for space-based agricultural production.  
• Informing scientific research in farming methods and environmental impact of different agricultural techniques. |
| International collaboration  | • Support to cross-border initiatives to manage global supply chains for agricultural products and services.  
• Support to international development and aid initiatives aimed at reducing poverty among subsistence farmers. |

34 Factories In Space (2020a), Robitzki (2019).
Climate and environmental protection

Definition

This cluster comprises all those activities in or enabled by space that are focused on managing the impact of human activity on the climate, weather, environment and ecosystems, to protect biodiversity, boost habitability and ultimately ensure the long-term sustainability of life on Earth.

For future space applications of relevance to the transition to clean and renewable energy sources (an important step to reduce carbon emissions), see Annex F on ‘Energy’.

Summary

Climate change, global warming and environmental degradation continue to produce adverse effects for organisations, communities and individuals in the UK and worldwide, including through rising sea-levels, declining biodiversity and increasing frequency of extreme weather events. As governments, industry and civil society seek to identify novel ways to support climate and environmental protection, space-based technologies may have several applications offering a mix of both incremental as well as potentially ground-breaking impacts.

Taken to an extreme, growing exploitation of space out to 2050 may provide an ‘insurance policy’ to sustain humanity as a species if ecological collapse, climate disaster or some other event (e.g. use of weapons of mass destruction) were ever to render the Earth uninhabitable in future. This is the logic behind SpaceX founder Elon Musk’s drive to make humanity a ‘multi-planet species’. Even in much less extreme scenarios, use of space offers significant potential benefits to the environment and the transition towards a green economy.

Terrestrial markets include the growing use of space-based services – particularly EO but also SATCOM and PNT for IoT devices, in conjunction with AI/ML – to enable real-time monitoring of indicators and phenomena relevant to climate and environment protection. This could contribute to early-warning, prediction, compliance with emissions goals and environmental standards, and mitigation and response strategies. The United Nations Framework Convention on Climate Change (UNFCCC) and international scientific community have defined 45 essential climate variables for monitoring to guide the global response, some 35 of which are measured from space.36

36 Hughes (2020).
In future other space-based markets beyond EO – including geo-engineering, terraforming and toxic/nuclear waste disposal – may represent novel high-reward opportunities, if realised. There are also substantial opportunities associated with space-based solar or fusion energy (see Annex F on Energy for discussion) or de-industrialisation of the Earth in favour of space-based manufacturing. This is a stated ambition of Amazon and Blue Origin founder Jeff Bezos, who envisages one day moving all heavy industry to space to ‘eventually turn Earth into a national park’. However, significant technological barriers remain to such ambitions, as well as cost, ethical and governance challenges.

### Relevant use cases

#### Space markets
- **Geo-engineering**: Future approaches to offset, slow or reverse the effects of climate change may include space-based solar geo-engineering and space-based solar radiation management (SRM). Geo-engineering could involve a range of techniques, such as marine cloud brightening, stratospheric aerosol scattering, or constructing space-based ‘sun-shields’ to block and reflect sunlight away from Earth.

#### Hybrid markets
- **Early-stage terraforming activities (Mars)**: Terraforming entails the ‘transformation of a planet so as to resemble the Earth so that it can support widespread life’. This would include a warming phase (brining temperatures up to a value closer to Earth’s temperatures), and an oxygenation phase (altering the CO2 atmosphere in Mars) to adapt the local climate to human life. While full terraforming of Mars is unlikely before 2050, initiating what is likely to be a decades-long process may be feasible and a prudent long-term investment, with huge returns.

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37 Stone (2019).
38 Harvard’s Solar Geoengineering Research Program (n.d.).
41 Kaku (2018).
**Future uses of space out to 2050 - Technical annex**

- **Nuclear and toxic waste disposal in space**: Improvements in the cost, safety and reliability of future space launch operations (or use of alternative means, e.g. elevators) may support the disposal of toxic substances in space, including radioactive waste. This would consist of solidifying and embedding waste in an explosion-proof vehicle, and subsequently launching into orbit and away from the Earth, including potentially into the Sun for complete destruction.43

- **Space support to process optimisation and waste reduction**: SATCOM and PNT may be used to facilitate waste disposal and reduction on Earth through IIoT, as well as the reusing and repurposing of organic and inorganic waste to reduce payloads from Earth to support space habitats and missions.44

### Terrestrial markets

- **Meteorological modelling and prediction**: EO may be used for real-time monitoring of weather and climate trends, including early warning and prediction of extreme weather events such as storms and hurricanes. EO data also contributes evidence to scientific and policy decisions on climate change.45

- **Atmospheric sensing**: Emerging space technologies may be used to monitor and measure ground phenomena through developments in the ionosphere. This could be used in the monitoring and prediction of earthquakes and volcanic eruptions, as well as mining operations, among others.46

- **Greenhouse-gas monitoring**: Space technologies including EO may be used to monitor emission levels as well as natural-gas leaks. This could help fulfil monitoring, reporting and verification requirements of UNFCCC frameworks.47

- **Oceanic and polar ice-cap monitoring**: Space-based technologies may also support climate change mitigation efforts through monitoring of oceanic and polar ice caps.48

- **Pollution monitoring**: EO may be used to assess the condition and extent of air as well as water pollution in rural as well as urban areas, including through improved monitoring of rural diffuse pollution (RDP) from agriculture.49

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43 Coopersmith (1999).
44 Sadlier & al. (2018); Jucha (2016).
45 Greenblatt & Anzaldua (2019).
46 The Economist (2020).
47 Morgan Stanley (2019b); Davies & Kerr (2018).
### Resources observation and management

EO data may provide insights supporting agricultural production, fisheries, forestry and freshwater management. Satellite data could help cut farms’ water use by 18–30 per cent, for example.

### Monitoring environmentally harmful or illicit activities

EO may support environmental protection through monitoring of environmentally harmful or illicit activities, such as illegal logging, animal poaching, fires and mining.

### Ecological and wildlife monitoring

Space technologies such as EO, SATCOM and PNT may be used to monitor wildlife habitats and nature reserves for environmental protection (for example, enabling virtual fencing).

### Marine environment monitoring

Space-based sensing and monitoring systems could be used to support marine environmental observation, including monitoring pollution (e.g. oil spills), fisheries, hydrography and bathymetry.

### Biomass measurement for offsets

EO data may be used to measure and monitor biomass and biodiversity in natural habitats, e.g. to identify carbon capture and offsets in support of meeting UNFCCC emissions targets and ‘net-zero’ goals.

### Natural disaster observation, early warning and relief

EO, SATCOM and PNT can be combined with technologies such as AI/ML to improve capacities for risk monitoring, forecasting and early warning of natural disasters, including earthquakes, volcanoes, wildfires and floods. They can also support mitigation, response and recovery operations.

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**Main actors**

Space-based applications for climate and environmental protection necessarily interest a wide range of different actors, with national governments, the private sector, civil society and individual members of the public all representing important stakeholders in a healthy environment. In the United States, current efforts to advance the above-described use cases include various NASA programmes exploring the potential for enhancing EO’s role in environmental management (e.g. ICESat-2 for polar ice-cap monitoring).

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50 Greenblatt & Anzaldua (2019).
51 Hughes (2020).
52 Greenblatt & Anzaldua (2019).
56 Hughes (2020).
In Europe, the ESA has a dedicated Climate Office and various programmes running through the ESA Climate Change Initiative. This aims to ensure that ‘full capital is derived from ongoing and planned ESA missions, including ERS, Envisat, the Earth Explorer missions, relevant ESA-managed archives of Third-Party Mission data and the Sentinel constellation’ as well as any future missions. In the UK, the Satellite Applications Catapult set ‘Sustainable Development’ and ‘Geospatial Intelligence’ as two of its focus areas. It also supports development of the Earth and Sea Observation System (EASOS), a decision-support platform that fuses satellite and terrestrial data to tackle challenges such as marine, flooding and fires watch, and to address the UN Sustainability Development Goals.

A number of leading academic research centres are also actively involved in exploring the feasibility, cost and impact of the more ambitious geo-engineering projects – such as solar shades – including the Oxford Geoengineering Programme and Harvard’s Solar Geoengineering Research Program. Technologies for climate and environmental monitoring have also demonstrated potential spillover utility in the defence and security domain, leading to engagement from relevant stakeholders such as the US Defense Advanced Research Projects Agency (DARPA), which has recently furthered development of atmospheric sensing through its AtmoSense (Atmosphere as a Sensor) programme, including support from academic and commercial institutions.

<table>
<thead>
<tr>
<th>Value proposition to end users</th>
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<tr>
<td>Government (civil)</td>
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<td>Government (military)</td>
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59 Climate Change Initiative (n.d.).
60 Oxford Geoengineering Programme (n.d.).
61 Harvard’s Solar Geoengineering Research Program (n.d.).
62 The Economist (2020).
63 Sadlier et al. (2018).
64 Cox et al. (2020).
Civil (commercial) • Support for industry compliance with emission targets and environmental regulations. • Improved risk assessment capabilities and insurance against climate-related risks to infrastructure and supply chains, leading to new ‘green’ products in sustainable finance. • New opportunities associated with geo-engineering in space and carbon offsets on Earth using EO biomass monitoring. • Space-enabled services in support of wider innovations in the green technology sector and emerging green economy.

Civil (other) • Advances in scientific research on climate change through better information, data gathering and analysis. • Advances in scientific research on ecology and wildlife, and space-based support to global and local conservation efforts. • Support for national and international climate change and environmental advocacy activities. • Support for Non-Governmental Organisations (NGOs) and civil society in disaster prevention and relief, including aid missions in disaster-affected environments.

Consumers • Increased safety and resilience against natural disasters and extreme weather events. • Incentives for consumer spending in compliance with ethical and environmental standards, given enhanced EO monitoring. • More informed public discourse on socio-political impacts and responses to climate change given use of space data.

Estimate of timeframes

The timeframes for different space-based applications in climate and environmental protections are wide-ranging and their future realisation will be dependent on a series of variables. Several EO-based applications – such as weather prediction and climate monitoring – have been in use for 30 years, and have resulted in tangible benefits for government and industry stakeholders, as well as consumers. These can be expected to mature further in the 2020s and 2030s as launch costs fall, on-board sensors improve (e.g. with advances in machine vision, optics, radar, lidar and other techniques), global coverage and redundancy increases (e.g. using mega-constellations of smallsats in LEO), and AI/ML and Big Data technologies improve to enable enhanced real-time analysis. Beyond 2030, developments may enable other types of monitoring (e.g. greenhouse gas monitoring), as existing technical barriers to direct measurement of point-source emissions are overcome. In total, UKspace estimate that 15,100 green jobs could be created in the UK space sector by 2030, potentially one-fifth of the total new green jobs across the national economy.

Timelines for larger scale projects – such as solar shades – are uncertain, given the scale, complexity and cost of such initiatives. Existing estimates for the timelines of other game-changing applications, such as Martian terraforming, range from 50 to 100,000 years, given the current lack of advanced techniques to support oxygenation processes.\(^\text{68}\)

**Drivers and enablers**

Many of the terrestrial markets utilising EO and other space-based technologies may benefit from advanced image processing and feature extraction capabilities, including automated or semi-automated processes enabled by AI/ML techniques.\(^\text{69}\)

Turning to more ambitious projects, despite the uncertainties concerning the ethical and governance challenges associated with geoengineering, a number of environmental groups as well as governments and national stakeholder groups have begun increasing support for geoengineering research. This could contribute to advances in the affordability and capability of the underlying technologies, as well as reducing uncertainties concerning the costs, benefits and potential impacts.\(^\text{70}\) While prospects for terraforming are currently limited, advances in synthetic biology and other biotechnologies may enable faster advances, particularly in processes supporting the oxygenation phase of terraforming.\(^\text{71}\)

**Potential barriers and challenges to implementation**

Several of the space-based applications within the climate and environmental protection cluster, including solar geoengineering and solar waste disposal, are challenged by high levels of uncertainty concerning the costs, ethics, safety and benefits of the technology.\(^\text{72}\) The business case for such drastic measures is also not clear whilst other comparatively low-cost and simple initiatives (e.g. greenhouse-gas reduction through reducing air travel, investing in solar and wind power, and encouraging walking, cycling and electric vehicles) have yet to be fully implemented or shown to fail.

Solar geoengineering poses additional governance risks that may ultimately undermine climate and environmental protection efforts. While the aggregate global impacts of geoengineering may be positive, local impacts could vary, producing substantial governance challenges and even the potential for conflict or hostile action against the solar shade.\(^\text{73}\)

Additionally, geoengineering efforts may distract resources and efforts away from existing efforts to cut emissions (potentially encouraging a culture of reliance on space-based solutions to provide a ‘deus ex machina’ to climate change, rather than making meaningful behavioural changes at the individual or organisational level). Also, geoengineering would not reduce the level of carbon dioxide in the atmosphere nor address many of the high-level challenges of climate change besides global warming, including ocean acidification.\(^\text{74}\)

Due to the perceived risks, public and political support for such markets may be limited, at least in the near future. While such barriers may be less relevant in relation to more incremental uses of space (e.g. EO for monitoring), other challenges persist. These include regulatory barriers and a lack of commercially accessible sensor networks.\(^\text{75}\)

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\(^{68}\) Berliner & McKay (2017).

\(^{69}\) Davies & Kerr (2018).

\(^{70}\) Harvard’s Solar Geoengineering Research Program (n.d.).

\(^{71}\) Berliner & McKay (2017).

\(^{72}\) Coopersmith (1999); Harvard’s Solar Geoengineering Research Program (n.d.).

\(^{73}\) Harvard’s Solar Geoengineering Research Program (n.d.).

\(^{74}\) Harvard’s Solar Geoengineering Research Program (n.d.).

\(^{75}\) Catapult Satellite Services (2017z).
### Summary of potential impacts and implications for the space economy

<table>
<thead>
<tr>
<th>Category</th>
<th>Impacts and Implications</th>
</tr>
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</table>
| **Prosperity**                  | • Supporting transition to a green economy, and creating new intellectual property, products, services and other benefits (e.g. exports, employment, innovation spillovers).  
  • Increasing GDP growth through mitigation of negative economic impacts of climate change (e.g. natural disasters).  
  • Supporting risk management, insurance and compliance with relevant regulations across global supply chains.  
  • Promotion of new EO-based consumer markets for environmental monitoring and other services. |
| **Environment & net-zero economy** | • Reducing climate change impacts, including rising temperatures and air and water pollution, and strengthening existing climate and environmental protection efforts.  
  • Providing implementation support to monitoring, reporting and verification of UNFCCC emissions targets and other international frameworks or national legislation and policies.  
  • Increasing investment in green economy leading to innovation and economies of scale that reduce cost of green technology.  
  • Supporting protection of natural habitats and wildlife, including conservation efforts for endangered species.  
  • Enabling long-term de-industrialisation of the Earth through use of space-based resources, energy and manufacturing. |
| **National security & defence**  | • Addressing direct impact of climate change on defence infrastructure and operations at home and abroad.  
  • Strengthening of national and societal resilience and ability to respond to climate change and natural disasters.  
  • Addressing the strategic implications of climate change and emerging security threats, e.g. due to resource scarcity. |
| **Science & discovery**         | • Advancing scientific techniques and understanding of the drivers and impacts of climate and environmental change.  
  • Providing evidence for scientific support to policymaking at the national level.  
  • Providing the basis for terraforming other planets and establishing more sustainable research facilities beyond Earth. |
| **International collaboration**  | • Supporting international climate cooperation, including existing frameworks such, as UNFCCC.  
  • Providing evidence for scientific support to policymaking at the international level.  
  • Providing opportunities for multinational cooperation on space-enabled green technologies to address common challenges arising from climate and environmental change. |
## Annex C. Construction, repair and engineering

### Definition
This cluster comprises all those activities in or enabled by space that are focused on designing, building and maintaining large structures – such as buildings and other physical infrastructure – to provide shelter and the basis for efficient movement of people, resources and goods around the built environment.

Relation to other clusters: for future space applications relating to the extraction of raw materials for use in construction projects, see Annex G on ‘Extractive industries’.

### Summary
Construction is, behind energy, the second-largest industry on Earth. Alongside energy production, transmission and storage, construction similarly plays a crucial enabling role for all other economic activity, creating and maintaining structures for residential, industrial and other purposes. It is therefore projected to be a highly attractive and important industry in space as well.

In the near term, the focus is on servicing satellites, space stations and telescopes, as well as experimenting with and refining technologies for robotic assembly of ever larger and more complex components and structures in-orbit. In the longer term, enhanced capabilities for orbital, lunar or Martian construction of habitats, solar farms, resource mines, factories, spacecraft and other assets is needed to reduce humanity’s reliance on sourcing every object it uses in space from Earth. Space-based construction, including on-orbit servicing and orbital self-assembly, have thus been described as a ‘master enabler to create the architectures needed to conquer the next frontiers in space’.

While many technical and cost barriers are likely to be addressed through advances in existing technologies, the more ambitious future plans (e.g. construction of orbital megastructures or large-scale lunar or Martian colonies) may require novel systems approaches to efficiently and successfully utilise new technologies for resource extraction, manufacturing, assembly and through-life support.

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76 Landon & Schneider (2017).
77 NASA (2010).
**Relevant use cases**

<table>
<thead>
<tr>
<th>Space markets</th>
<th>• Construction of commercial and residential megastructures: Space-based construction projects may include orbital megastructures that contain hotels, factories, and permanent habitats. The emergence of orbital real-estate markets may one day result in the construction of cities in space.(^\text{78}) In the nearer term, on-orbit or in-situ construction of satellites, spacecraft and settlements using a mix of local resources and limited supplies from Earth may reduce overall costs by reducing the need to launch materials into orbit.</th>
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<tr>
<td></td>
<td>• Robotic orbital, lunar or planetary construction: Robotic assembly fleets may be used in combination with high-quality metallic feedstocks on civil and commercial construction projects, including in-space assembled telescopes, manufacturing facilities and solar farms.(^\text{79})</td>
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<td>• 3D printing of lunar bases: Space-based construction may include 3D printing and automated assembly of structures on the Moon from on-site materials, such as lunar regolith.(^\text{80})</td>
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<td>• 3D printing of Martian bases: Additive manufacturing techniques may also be applied to the construction of bases and habitats on Mars. Current concepts for Martian habitats envision habitation modules, scientific structures, mining equipment and pressurised rovers for in-situ transport.(^\text{81})</td>
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<td>• On-orbit satellite servicing: On-orbit servicing entails the ‘servicing, refuelling, repairing and even upgrading satellites that are in orbit’, frequently with the use of specialised robotic spacecraft.(^\text{82}) On-orbit servicing has been increasingly emphasised as a key enabler for space exploration.(^\text{83}) It is also closely associated with improved management of space junk, keeping satellites fuelled, operable and on-orbit for longer.</td>
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<td>• Space-based maintenance and repair services: Space-based maintenance and repair services for spacecraft and structures such as propellant refineries, asteroid mines and solar power plants would increase their operational lives and efficiency, as well as reducing the financial and time costs associated with returning to Earth for repairs or replacement parts.(^\text{84})</td>
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78. Landon & Schneider (2017).
79. Landon & Schneider (2017); Siegler et al. (2019).
81. Farkas (2016).
82. Choudhary (2019).
83. Choudhary (2019).
84. Landon & Schneider (2017).
### Hybrid markets

- **Connectivity for smart infrastructure**: Space-based technologies such as SATCOM and PNT should play a major role in enabling the construction of ‘smart’ cities, buildings and infrastructure with embedded connectivity and sensors – whether these structures are on Earth or in space.

### Terrestrial markets

- **Connectivity for construction IIoT**: Space-based technologies may provide connectivity for construction IIoT, with potential impacts on Building Information Modelling (BIM), reducing costs and improving employee Health and Safety through real-time monitoring of wearable sensors and other data.\(^{85}\)
- **EO for building and infrastructure monitoring**: Space-based assets – including EO satellites (fitted with optical, radar and lidar sensors) – may be used for monitoring infrastructure, which could support predictive maintenance (e.g. in response to subsistence).\(^{86}\)
- **Urban planning and real-time monitoring**: Space-based services may lead to advanced urban planning solutions, including subsidence monitoring, precision and urban agriculture and construction projects, energy-loss detection, and waste management/recycling solutions.\(^{87}\)

### Main actors

Several nations, including the United States, Russia and China, have expressed ambitions for space-based construction of space bases and habitats. China’s current ambitions include the establishment of a ‘Moon colony’ by 2030, with Russia aiming to achieve this by 2040. Space agencies – including NASA and ESA – have also advanced additive manufacturing projects, including NASA’s ‘3D-printed habitat challenge’ and ESA’s additive manufacturing of objects built from artificial lunar regolith.\(^{88}\) In 2020, NASA also awarded a $142m contract to Maxar Technologies to manufacture a spacecraft beam in orbit and robotically assemble a communications antenna, a technology demonstration taking place on NASA’s Restore-L satellite, itself designed to service and refuel other satellites in LEO.\(^{89}\)

In the UK, ‘Construction and Engineering’ is one of the stated priorities for the Satellite Applications Catapult within the ‘Exploring New Markets’ focus area, primarily with a focus on the terrestrial sector.\(^{90}\)

### Value proposition to end users

- **Government (civil)**
  - Enhanced resilience, performance and operational lives for space-based assets and services (e.g. EO satellites).
  - Greater resilience of terrestrial infrastructure, including critical infrastructure.
  - Space-based monitoring of infrastructure can support resource-investment decisions.\(^{91}\)

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85 Ball (2020).
86 Catapult Satellite Applications (2020a).
87 Catapult Satellite Applications (2017k).
88 Tangermann (2018a).
89 NASA (2020a).
90 Hilton (n.d.).
91 Catapult Satellites Applications (2020a).
Government (military)

- Greater resilience and adaptability of satellites for different mission purposes to support military needs.
- Reduced reliance on access to space from Earth (e.g. if launch sites are compromised or LEO is congested by debris) through rapid construction of assets in space as alternative.
- Support in critical infrastructure protection (CIIP).

Civil (commercial)

- Enabling of other space markets, including space habitats, solar energy farms, asteroid mines and space-based factories.
- Potential to recycle telescopes for orbital real-estate uses increases economic viability of space-based construction.\(^\text{92}\)
- Improving terrestrial infrastructure-investment decisions and risk assessment, as well as construction industry productivity.\(^\text{93}\)

Civil (other)

- Facilitating advances in deep-space exploration, science and research through construction of necessary research sites, waystations and other infrastructure.

Consumers

- Increased economic viability of potential space habitats.
- Predictive infrastructure maintenance may ensure safer terrestrial infrastructure for users.

**Estimate of timeframes**

As of 2020, actors including NASA and the ESA have already commenced experimentation with crewed missions (involving spacewalks) and close proximity satellite missions for on-orbit servicing and repair of space objects, including the ISS and the Hubble Space Telescope.\(^\text{94}\) One NASA-backed project – the Archinaut One satellite designed by Made in Space – has been awarded $73.7m to manufacture and assemble spacecraft components on-orbit, with plans to launch by the mid-2020s.\(^\text{95}\)

More ambitious space-based construction projects are predicted to commence by the 2030s, driven by advances in space robotics and additive manufacturing, as well as by the powerful economic logic of sourcing construction materials in space rather than paying to launch them from Earth. Projections suggest that visions for large-scale structures and habitats being built by automated robotic systems, largely or exclusively using in-situ resources – including lunar and Martian bases constructed from local regolith and other construction materials – may be realised by 2040, and further refined thereafter.\(^\text{96}\)

Advocates of a ‘bootstrapping’ approach to space colonisation suggest that exponential growth may then be possible once the key underlying technologies have been matured by mid-century. An initial small fleet of automated, self-repairing robots would build a series of resource extractors, solar energy farms and manufacturing facilities (e.g. on the Moon) using available local resources. These would in turn build more robots, which would build more factories, which would build more robots – leading to a continuing cycle with effectively limitless resources for construction of ever larger fleets or structures.\(^\text{97}\)

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\(^\text{92}\) NASA (2010).
\(^\text{93}\) Catapult Satellites Applications (2020).
\(^\text{94}\) Billings (2018).
\(^\text{95}\) Hedmond (2019).
\(^\text{96}\) Tangermann (2019).
\(^\text{97}\) Kaku (2018).
Drivers and enablers

Although costs of launch may be an important consideration for space-based construction efforts (determining whether it is more cost-efficient to build from in-situ resources or just launch modules or fully assembled assets from Earth), future space-based construction may fundamentally rely on capabilities for automated robotic assembly. This is due to the limited space on launch vehicles as well as the enduring high cost of launch (unless, for example, a space elevator was feasible by 2050).

The viability of future in-space construction, including lunar or Martian habitats, may depend on advances in robotics, autonomy and energy systems, as well as extractive industries and the ability to harness H2O (for oxygen and hydrogen as fuel, and water) and other essential resources in-situ. Current concepts for Martian bases, for example, envision energy to be supplied through small nuclear fission reactors in place of solar power systems to ensure sufficient energy to power large-scale construction and manufacturing efforts.98

Continuing scientific and technological advances in complex materials, including self-repairing materials and smart materials that can change shape in response to a given stimulus (e.g. an electrical charge), may also play an important role in enhancing the complexity and affordability of the structures that can be constructed on-orbit or on the Moon, Mars or other bodies.

Finally, clarification of governance, legal and regulatory issues around land ownership and property rights in outer space should also be an important factor in driving investment, alongside enduring political and commercial competition in an ongoing ‘race for space’.

Potential barriers and challenges to implementation

There are several technical and economic barriers to in-space construction and engineering. Currently, repair capabilities are limited to those operated by humans or remotely by relatively simple robotic systems, and thus advances in more autonomous and capable robotic spacecraft may be necessary to enable the realisation of larger scale construction projects.99

While applications such as on-orbit servicing may require relatively little new technology, they require ‘a disciplined systems approach in order to use existing technologies successfully and effectively’.100 Mission lifetimes are also ‘fuel or cryogen limited’, meaning even refuelling and repair systems will create their own demands to be refuelled and repaired over time.101 The viability of innovative construction techniques, such as additive manufacturing, may also be challenged by the possible inability of 3D-printed objects and structures to withstand the stresses of space environments.102

The economic challenges associated with space-based construction – such as on-orbit servicing – currently include the high cost of maintenance or upgrade systems, which are required for on-orbit servicing. As such, only a limited number of larger commercial systems may be economically viable for on-orbit servicing in the near term, since it may remain simpler and more cost-efficient to deorbit and replace lower value satellites rather than repair them in-situ.103

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98 Farkas (2016).
99 Siegler et al. (2019).
100 NASA (2010).
101 Siegler et al. (2019).
102 Letzter (2016).
103 NASA (2010).
<table>
<thead>
<tr>
<th>Category</th>
<th>Impact</th>
</tr>
</thead>
</table>
| **Prosperity**                        | • Enabling construction of satellites, spacecraft and facilities to benefit a wide variety of markets.  
• Increasing market opportunities for companies specialising in space robotics, construction, servicing and repair.  
• Increasing resilience and operational lives for space-based objects and therefore increased value-for-money and economic returns on initial investment.  
• Improvements in productivity of terrestrial construction industry, as well as reduced costs from building and infrastructure maintenance or recapitalisation, through use of space-enabled services for real-time monitoring and predictive maintenance. |
| **Environment & net-zero economy**    | • Construction in support of advances in environmental science and space-based energy markets.  
• Construction of larger space-based energy systems, e.g. on-orbit or lunar solar farms.  
• Use of EO and other satellite-enabled services to improve and monitor the environmental impact of the construction industry.  
• Reduced reliance on extraction and exploitation of terrestrial resources, opening up the longer term potential for the de-industrialisation of the Earth and shifting of focus to resource extraction and construction of space. |
| **National security & defence**        | • Reduced risk of space debris through on-orbit servicing (avoiding the proliferation of abandoned or inoperable satellites).  
• Resilience and repair of satellites and other space-based services for national security and defence.  
• Reduced reliance on access to space (e.g. if launch sites are compromised or LEO too congested with debris) given ability to construct assets in space if needed. |
| **Science & discovery**                | • Reduced cost and risk compared to deploying structures such as telescopes on individual launch vehicles.  
• Ability to construct larger and more capable telescopes and satellites for scientific discovery through in-orbit assembly.  
• Additive manufacturing of deep-space exploration habitats. |
| **International space collaboration**  | • Improvement of overall robustness and resilience of space-based assets and services on joint collaborative missions.  
• Enhanced opportunities for collaboration around space robotics and other technologies for on-orbit servicing.  
• Enhanced opportunities for collaboration on space-based construction projects, including on the Moon and Mars. |

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104 NASA (2010).  
105 Siegler et al. (2019).  
106 Tangermann (2019).  
107 Choudhary (2019).
## Annex D. Culture, tourism and entertainment

<table>
<thead>
<tr>
<th><strong>Culture, tourism and entertainment</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition</strong></td>
</tr>
<tr>
<td>This cluster comprises all those activities in or enabled by space that are focused on providing opportunities for amusement, enjoyment and artistic appreciation, shaping ideas, customs and social behaviours, and thereby contributing to humanity’s collective artistic and intellectual achievement.</td>
</tr>
<tr>
<td><strong>Summary</strong></td>
</tr>
</tbody>
</table>
| Space has long been a source of wonder, excitement and inspiration, playing a prominent role in arts, culture and entertainment. This inherent capacity to fascinate could bring more intangible benefits (e.g. cultural appreciation) as well as direct economic benefits, and the opportunity for governments and commercial actors to exert influence (‘soft power’) within global society and media.  
Future space-enabled markets in comprise a wide range of services providing transport to space (i.e. orbital or suborbital space tourism), as well as broader cultural and entertainment activities on or utilising space objects. Space-based infrastructure and services may also enable new kinds or improvements in existing terrestrial markets, such as multimedia, film production and gaming, including games facilitated by virtual reality (VR)/augmented reality (AR)/mixed reality (MR) technologies.  
While space-based culture and entertainment represents potentially highly attractive markets for the commercial as well as civil space industry, potential barriers include high costs of space travel, uncertain future public interest in space-faring (influencing demand), or nationally determined barriers, such as lack of expertise in civilian commercial space-flight. Space-based tourism, culture and entertainment will also necessitate reconsideration of relevant legal and regulatory provisions, as well as the existence of plans to deal with potential detrimental impacts for the orbital environment (by generating space debris) and conflicts with civil and military space operations.  
Out to 2050, growing use of space is also likely to have complex but profound cultural and normative impacts on both space-based and terrestrial society, shaping perceptions of humanity’s place in the Universe, its artistic and design sensibilities, and its appreciation for different ideological standpoints (e.g. on political authority or the environment). |
<table>
<thead>
<tr>
<th>Space markets</th>
<th>Relevant use cases</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Space tourism (suborbital):</strong> Commercial suborbital flights (below the Karman line at 100km altitude) utilising supersonic rocket technology, spaceplanes or high-altitude balloons.(^{108})</td>
<td></td>
</tr>
<tr>
<td><strong>Space tourism (orbital):</strong> Space tourism services may evolve beyond suborbital flights to include space travel in Earth’s orbit or beyond (e.g. with trips to the Moon or further afield). Orbital flight necessitates higher kinetic energy trajectories, indicating greater technical and economic barriers than suborbital space tourism.(^{109})</td>
<td></td>
</tr>
<tr>
<td><strong>Space-based hospitality (orbital or lunar megastructures):</strong> Tourist visits to space may drive the development of a wider ecosystem in space, for instance in the form of dedicated habitats. Commercial space markets may include the construction of large hospitality and real estate structures, including tourist ‘hotel’ destinations.(^{110})</td>
<td></td>
</tr>
<tr>
<td><strong>Space-based filming and gaming or video content production:</strong> Space stations, satellites and spacecraft may be utilised for the production of cultural and entertainment content, for example audio-visual material for films and gaming.(^{111})</td>
<td></td>
</tr>
<tr>
<td><strong>Space-based or -enabled art installations:</strong> This may include the use of commercial spacecraft for the launch of artistic satellites, artificial stars and other art installations, along with the construction of monuments by state or private actors.(^{112})</td>
<td></td>
</tr>
<tr>
<td><strong>Space burials:</strong> As launch costs fall, space burials may become an increasingly viable and popular way of disposing of one’s remains on or beyond Earth’s orbit.(^{113})</td>
<td></td>
</tr>
<tr>
<td><strong>Space conservation and heritage:</strong> Future uses of space may include designated space conservation and heritage sites, for example the Apollo 11 landing site and other lunar or Martian locations of natural beauty or cultural significance.(^{114})</td>
<td></td>
</tr>
<tr>
<td><strong>Space-based cultural or religious facilities:</strong> A changing role of religion in shaping and being shaped by public attitudes towards space-faring may lead to the establishment of cultural and religious facilities in space. This may benefit the promotion of future space exploration as a form of pilgrimage and evangelism, and shape attitudes towards stewardship of ‘the heavens’ among religious communities.(^{115})</td>
<td></td>
</tr>
</tbody>
</table>

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110 Landon & Schneider (2017).
111 Grush (2020).
112 Yalcinkaya (2019); (2018).
113 Hollingham (2014).
115 David (2014).
• **Space-based (extreme) sports**: Orbital space tourism and the construction of extra-terrestrial commercial megastructures may include the construction of sports arenas and services for space-based sports (for exercise, recreation or broadcast).\(^{116}\) These could exploit zero or low gravity to facilitate physical feats unlike any sport on Earth. Other entertainment activities may include use of rovers and space-yacht cruises.\(^{117}\)

• **Space-based marketing**: Future advertising in or using space may entail various forms of marketing, including publicity stunts (in the model of Elon Musk’s Tesla roadster launch),\(^ {118}\) display of logos on spacecraft and advertisement panels.\(^ {119}\)

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\(116\) Kaku (2018).
\(117\) Greenblatt & Anzaldua (2019).
\(118\) David (2018).
\(119\) De Gouyon Matignon (2019).
\(120\) Augmented Reality can be defined as ‘digital content [placed] on top of the real world by adding graphics onto a display such as a smartphone or a headset that sits between the user and the world’. Mixed Reality is differentiated from Augmented Reality in that spatial mapping techniques (infrared, motion tracking) are used to ‘profile a space and allow digital content to sense and interact with the real world’. Source: Catapult Satellite Applications (2017).
\(121\) Catapult Satellite Applications (2017).
\(122\) Harris (2009).
Terrestrial markets

- **Connectivity for entertainment and media**: Space-enabled telecommunications services may provide next-generation connectivity for terrestrial entertainment and media markets, including multimedia entertainment.\(^{123}\)

### Main actors

Several major commercial actors and newer start-ups have directed their efforts at achieving low-cost access to space, thus facilitating space tourism in the near-term and the wider use of space for cultural and entertainment purposes in the mid and long-term.\(^{124}\)

This includes Virgin Galactic and Blue Origin, which have conducted suborbital flights on reusable rockets with the aim of inaugurating their first tourist flights in the 2020s.\(^{125}\) The first orbital ‘tourism’ flights are currently being pursued by SpaceX and Space Adventures.\(^{126}\) Billionaire Japanese retail entrepreneur and art collector Yusaku Maezawa is financing the #dearMoon project, a lunar tourism mission and art project that aims to fly a team of artists on a circumlunar trajectory around the Moon on a SpaceX Starship, perhaps as early as 2023.\(^{127}\) NASA has also engaged in discussions with actor Tom Cruise regarding filming a movie aboard the International Space Station.\(^{128}\)

Looking towards 2050, the growth of the space economy and related arts, culture and entertainment markets promises greater engagement from commercial organisations, individual content creators and civil society organisations including, for example, arts councils funding performances in or enabled by space, or non-profits advocating for recognition of heritage sites.\(^{129}\)

Alongside private and commercial actors, governments also have a role to play as custodians of national culture: for instance, the US Government and NASA have recognised the growing need for conservation frameworks as space becomes more widely and intensively used, with the White House issuing recommendations for protecting the Apollo landing sites in 2018.\(^{130}\)

### Value proposition to end users

- **Government (civil)**
  
  - Production of popular media about space or produced in space may inspire students in STEM fields, as well as recruitment of engineers and scientists by government agencies and/or the commercial space industry.\(^{131}\)
  
  - Successful space tourism, arts, culture or entertainment industries may bring significant economic benefits as well as international standing and influence (‘soft power’).\(^{132}\)

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124 Carter (2019).
125 Mann (2020).
126 O’Kane (2020).
128 Foust (2020).
129 Hanlon (2019).
131 Grush (2020).
132 Catapult Satellite Applications (2017y).
<table>
<thead>
<tr>
<th>Government (military)</th>
<th>• Satellite EO data and advances in AR/VR/MR may be applied in highly realistic military training and simulation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Civil (commercial)</td>
<td>• The future space hospitality market — including space tourism and space-in-space leasing — is estimated to generate a $37bn economy out to 2030, with scope for much more significant growth to 2050 as space technology matures.133</td>
</tr>
<tr>
<td>Civil (other)</td>
<td>• Space-based markets may provide an impetus to various advocacy movements, including cultural, heritage and political stakeholder groups and artistic movements.</td>
</tr>
</tbody>
</table>
| Consumers            | • Greater access, reduced cost and improved quality of culture and entertainment services (e.g. better connectivity, better quality of audio-visual content in films and games).  
  • Cultural and artistic appreciation. |

**Estimate of timeframes**

While several commercial actors are busily implementing plans for suborbital space tourism, advances in commercial orbital spaceflight have been slower. Nonetheless, the first commercial orbital ‘tourism’ flights are currently planned for as early as 2021/2022.134 It is likely that space tourism may become viable in the 2020s — assuming technical, regulatory (e.g. liability) and safety issues can be overcome — expanding to a wider customer base in the 2030s and 2040s as costs fall and technology improves. Progress in realising other visions for the cultural and artistic exploitation of space will depend also on developments in other markets, e.g. space-based construction and resource extraction to provide the basis for sizeable orbital, lunar or Martian settlements in the 2030s and 2040s — with viable human settlement being a prerequisite for space-based sports or permanent religious and cultural installations.

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133 Landon & Schneider (2017).  
134 O’Kane (2020).
Drivers and enablers

The falling costs of launch and associated developments in reusable launch technologies represent a key enabler for space-enabled markets, including in arts, culture and entertainment.

Like space bases and habitats directed at space exploration or other uses, commercial lunar or orbital habitats used for culture and entertainment also depend on the availability of several key related services, including energy generation, space-based manufacturing and robotics. Public awareness and interest in space-faring activities are also a key enabler for shaping the demand for space-based or space-related cultural and entertainment markets.

Existing research has also identified several specific enablers for a successful UK space tourism sector. These enablers include: i) early response, ii) ability to offer a range of space tourism possibilities, iii) synergy with other tourist services and options to create a package that can sell the UK as the preferred destination, and iv) the branding of operational and technical expertise of the UK.135 These enablers are further underpinned by the establishment of a favourable regulatory environment and availability of insurance services.136 Looking further out to 2050, the UK’s world-leading arts and culture sector (worth £10.8bn to the UK economy in 2019), may position it to exploit new opportunities associated with growing exploitation of the space domain.137

Potential barriers and challenges to implementation

Economic viability remains a key barrier for the realisation of cultural and entertainment-oriented uses of space, particularly orbital flight and all activities facilitated by orbital space travel (e.g. hospitality).

Specific challenges for the UK and its ability to develop a space tourism sector may include a lack of expertise and experience with commercial orbital or suborbital launches, as well as a lack of high-level public advocacy and support for space tourism (‘blue sky thinking’).138

The extensive risks associated with space travel, as well as technological advances in AR/VR/MR technologies may also lead to reduced demand for costly space tourism services, when highly realistic simulations can be produced much more flexibly, cheaply and safely.139

An increased quantity of activities and travellers in space also presents extensive governance challenges, given, for example, the increased likelihood of pollution and collisions due to the associated space debris, or the potential for cultural and entertainment initiatives to interfere with civil or military activities.140 Though international law currently lacks any provisions that would limit cultural and entertainment uses of space, future regulation and national legislation may seek to place limits on such activities.141

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135 Catapult Satellite Applications (2017y).
136 Catapult Satellite Applications (2017y).
137 Centre for Economics and Business Research (2019).
139 Catapult Satellite Applications (2017y).
140 De Gouyon Matignon (2020).
141 De Gouyon Matignon (2020).
<table>
<thead>
<tr>
<th><strong>Summary of potential impacts and implications for the space economy</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Prosperity</strong></td>
</tr>
<tr>
<td>• HM Treasury defines prosperity not in terms of narrow financial benefits, but also in terms of wider 'social value', with arts and culture – such as that enabled by use of space – contributing to the well-being of the general population.</td>
</tr>
<tr>
<td>• The space tourism industry is projected to carry an estimated £158m of revenue in the first 10 years, assuming a cost of £175k per seat. However, this could increase significantly out to 2050 as the sector matures and the audience widens.</td>
</tr>
<tr>
<td>• Orbital tourism may lead to spillover improvements in operational efficiencies, reusability, reliability and economies of scale for space flight, benefiting government users.</td>
</tr>
<tr>
<td>• Successful space-related arts, culture or entertainment industries may bring significant economic benefits. The UK may become 'a top ten tourist destination with the advantages that brings in developing a new sector'.</td>
</tr>
<tr>
<td><strong>Environment &amp; net-zero economy</strong></td>
</tr>
<tr>
<td>• Space tourism may lead to powerful shifts in attitudes toward the environment and social welfare and could become an important &quot;side benefit&quot; of a growing... industry.</td>
</tr>
<tr>
<td><strong>National security &amp; defence</strong></td>
</tr>
<tr>
<td>• EO, SATCOM and PNT may contribute to improved real-time and high-fidelity modelling, simulation and synthetic environments using AR/VR/MR, whether for training purposes or as operational planning and decision support tools.</td>
</tr>
<tr>
<td>• Popular cultural depictions of space may inspire new recruits to join the armed forces or pursue careers in relevant areas, e.g. STEM or aerospace industry.</td>
</tr>
<tr>
<td><strong>Science &amp; discovery</strong></td>
</tr>
<tr>
<td>• Advances in commercial suborbital spaceflight may bring scientific advances, including microgravity research.</td>
</tr>
<tr>
<td>• Popular cultural depictions of space may provide inspiration for a new generation of scientists and engineers.</td>
</tr>
<tr>
<td>• Gamification may support open- and citizen-science initiatives, e.g. involving the public in processing data for the purposes of space exploration and scientific research.</td>
</tr>
<tr>
<td><strong>International collaboration</strong></td>
</tr>
<tr>
<td>• Enhanced public awareness and support for international space collaboration through culture and popular media.</td>
</tr>
<tr>
<td>• Opportunities for collaboration on joint educational, artistic and cultural initiatives about or in space.</td>
</tr>
<tr>
<td>• Opportunities for collaboration in preserving sites of designated historical, cultural or religious significance.</td>
</tr>
</tbody>
</table>

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142 Catapult Satellite Applications (2017y).
143 Webber (2004).
144 Catapult Satellite Applications (2017y).
146 Mann (2020).
Annex E. Defence, security and safety

<table>
<thead>
<tr>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>This cluster comprises all those activities in or enabled by space that are focused on protecting people, interests and values by preventing, deterring and, where necessary, defeating attacks by hostile actors and managing other threats, risks and hazards that might endanger life or property.</td>
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</table>

Relation to other clusters: Activities in this area create a safe and stable environment for pursuit of the space use-cases outlined in all other clusters, contributing to security, influence and prosperity.  

<table>
<thead>
<tr>
<th>Summary</th>
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<tbody>
<tr>
<td>From the beginning of the space age in the mid-20th century, military organisations and defence research agencies have played a central role in promoting the development of the space sector, driving investment and innovation in rocket systems, spaceplanes and EO, SATCOM and PNT services as well as many of the underlying enabling technologies. This reflects a recognition by defence planners of the tactical, operational and strategic advantages offered by control and use of space as the ‘ultimate high ground’. Satellite systems and related advances in fields such as ICT provide the basis for modern digitalised and networked ways of warfare: enabling communications between military forces; navigation and targeting data for precision-guided munitions and vehicles; and surveillance and intelligence gathering on adversaries’ forces, movements and electronic signals.</td>
</tr>
<tr>
<td>Space is now recognised as an operational domain, alongside land, maritime, air and cyber, by most leading powers, along with the North Atlantic Treaty Organisation (NATO). Space-enabled applications also support a growing range of safety-critical systems (e.g. emergency communications and alert systems) in civilian vehicles, equipment and processes, as well as the emergency services. Looking out to 2050, the ongoing commercialisation of space is creating a range of new threats and opportunities for militaries, law enforcement, industry suppliers and other actors to provide products and services that promote defence, security and safety.</td>
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147 For more on the purpose and value of defence in all domains, see the Defence Value Proposition (DVP) developed for the UK Ministry of Defence and outlined in Black et al. (2020).


149 Banks (2019).
On the one hand, the continuing growth of the space economy offers the potential for relevant new missions and capabilities, such as improved secure communications (e.g. quantum-encrypted SATCOM), enhanced EO for real-time global surveillance, monitoring and protection of Critical National Infrastructure (CNI), support to military, police and humanitarian operations in austere environments, and even planetary defence to counter the dangers of incoming meteors or other threats.\footnote{150}

At the same time, the growing breadth and intensity of activities and actors in or through space poses significant new challenges from a defence, security and safety perspective. Falling launch costs and the democratisation of space – traditionally a domain dominated by the largest nation-states, and especially the US military – creates a more complex, multi-stakeholder environment that has implications for deterrence and management of the risks associated with accidental escalation or purposeful conflict.\footnote{151}

Debris management and removal is a key issue, and addressing it through improved SSA/SST and other means is a prerequisite for building a safer and more sustainable space ecosystem.\footnote{152}

Furthermore, the increasing dependence of many systems on Earth on space services – such as EO, SATCOM and PNT (see other clusters e.g. on ‘Finance and commerce’, ‘Logistics’ and ‘Manufacturing’) – also increases the threat that damage or disruption of space-based infrastructure could have cascading implications for the safety and function of many terrestrial systems. Securing space is therefore likely to become an increasingly indispensable and indistinguishable part of securing Earth out to 2050.\footnote{153}

There is a range of technical enablers and barriers that will determine the future of potential space-based defense, security and safety applications to 2050. These include the enduring challenges of innovation in this risk-averse sector, the impact of the growing availability of low-cost and fully reusable launch systems on the types of activities and actors operating in this increasingly congested domain, along with the uncertain future of space norms and other mechanisms for preventing conflict in space.

### Relevant use cases

| Space markets | Military operations in or against space: Nations and international law have largely sought to avoid militarisation and weaponisation of space (i.e. permitting the use of satellites for communications or to gather intelligence, but not to mount weapons). This includes the ban on space-based weapons of mass destruction (though not conventional arms) in the 1967 Outer Space Treaty (OST), and the unratified Moon Treaty’s proposed provisions governing military use of the lunar surface. However, out to 2050 various actors may conduct new types of military operation in or through this domain, either to target adversary’s space-based infrastructure (e.g. with anti-satellite (ASAT) capabilities, such as kinetic weapons, mines, directed energy weapons, cyberattacks, or other means) or use space-based capabilities to support military operations on Earth. |

\footnote{150} Stickings (2019).  
\footnote{151} Paulauskas (2020).  
\footnote{152} DIA (2019).  
\footnote{153} Black (2018).
- **Security services for space-based assets**: Commercial space security solutions – whether to prevent theft, physical attack, cyber intrusion or natural hazards (e.g. debris/meteor impacts) – may become increasingly profitable as the value of commercial assets and number of people in space increases.

- **Secure long-term storage for data and high-value items**: Space offers a potentially attractive location for long-term secure storage, far from most human activity and in controlled climatic conditions, for example to backup knowledge and maintain data-sets or DNA for future generations.\(^{154}\)

- **Debris management and removal**: Future debris management services may enable a safer space environment and reduce the growing risk of cascading collisions between objects rendering LEO unusable (the Kessler syndrome).\(^{155}\) This includes close proximity missions and other techniques for safely repairing, refueling, moving or deorbiting space objects.

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### Hybrid markets

- **Next generation SSA/SST**: Future innovation will enable improvements in data collection (e.g. using ground-based radar, lidar, optical and space-based sensors) and processing (e.g. using AI/ML) to provide improved detection and modelling capabilities and improved situational awareness.\(^{156}\)

- **Search and rescue**: New emergency beacon technology – using satellite-aided distress location services – can support improved accuracy of data location and quicker response times for SAR on Earth, while growing use of space (e.g. for tourism) entails a need for future SAR capabilities and missions in space.\(^{157}\)

- **Solar weather monitoring and early warning**: Along with debris monitoring, continuing development of systems for monitoring and mitigating the threats posed to astronauts, spacecraft and terrestrial systems (e.g. energy grids) from solar weather is likely to be a growing market and priority out to 2050.\(^{158}\)

- **Space-based C4ISTAR capabilities**: Space-based assets will contribute to enhanced command, control, communications, computers, intelligence, surveillance, target acquisition and reconnaissance (C4ISTAR) for military forces in all domains, facilitating multi-domain integration and joint warfighting.\(^{159}\) This draws together the benefits of EO, SATCOM and PNT.

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\(^{154}\) Factories in Space (2020b).

\(^{155}\) Greenblatt & Anzaldua (2019); Sputniknews.com (2018).

\(^{156}\) Lal et al. (2018).

\(^{157}\) NASA (2019b).

\(^{158}\) Los Alamos National Laboratory (2019).

\(^{159}\) Wald (2014).
• **Space-based cybersecurity**: Improvements in cybersecurity in and enabled by space ensures the protection of global communications infrastructure and other services – e.g. EO, PNT – that are paramount to military operations, financial markets and critical infrastructure for example.\(^{160}\)

• **Missile defence and early warning**: In addition to current and planned future capabilities for space-based detection of missile launches and trajectories, novel concepts out to 2050 envisage the use of space-based kinetic interceptors or directed energy weapons to facilitate missile defence.\(^{161}\)

• **Orbital weapons (kinetic)**: While WMD are illegal in space, conventional weapons are not; in future, certain actors may seek to gain an advantage by targeting opposing space systems or terrestrial targets with physical projectiles.\(^{162}\)

• **Orbital weapons (non-kinetic)**: To the end of neutralising or disrupting opposing space systems, future non-kinetic weapons launched from Earth or from orbit could enable jammers, dazzlers and microwave attacks on space assets.\(^{163}\)

• **Conventional Prompt Global Strike (weapons or suborbital deployment of forces)**: CPGS represents a long-standing ambition for the US military and others to have a long-range prompt-strike capability (e.g. employing hypersonic weapons or rapid deployment of special forces using suborbital flight) to allow time-sensitive attacks on high-value targets around the world, at the beginning of or during a conflict.\(^{164}\)

• **Monitoring and support to resilience of Critical National Infrastructure**: Potential opportunities exist for satellite services in critical infrastructure management and operation arising from current EO and PNT satellite data combined with new sensors (e.g. IoT), as well as with other devices, such as UAS.\(^{165}\)

• **Support to threat modelling, simulation and analytics**: Future advances in EO and other space capabilities may provide 3D scanning of outdoor environments to obtain location coordinates of objects with high accuracy. This would ultimately enable massive data real-time modelling and threat assessment and prediction with AI/ML, as well as creation of high-fidelity synthetic environments using AR/VR/MR for training or operational planning tools.\(^{166}\)

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160 Chatham House (n.d.).
161 Roberts (2019).
164 Woolf (2020).
165 Catapult Satellite Applications (2017h).
166 Catapult Satellite Applications (2017l).
• **Pervasive and verifiable EO to generate trusted ‘digital twin’ of Earth**: Related to the use of satellite data for modelling and simulation are ambitious visions to use space-based sensors, Big Data analytics, blockchain and other trust-enhancing technologies to establish a comprehensive and accurate ‘digital twin’, providing a verifiable ‘ground truth’ record of activity below on Earth.\(^{167}\) Combining advances in EO with new technologies and techniques for securing the integrity of data could help to counter disinformation and misinformation by exposing the reality of actors’ hostile actions. This could also have an inherent deterrent effect, encouraging restraint by actors due to the ‘panopticon effect’, i.e. the knowledge that any hostile behaviour will be exposed by constant global surveillance. This vision of a ‘digital twin’ for the Earth would represent a paradigm shift in both security and the economy, but also provoke major political, legal and ethical concerns.\(^{168}\)

**Terrestrial markets**

• **EO for next-generation sanctions, arms control and peacekeeping enforcement and verification**: EO services may be used to ensure compliance with arms control agreements, such as through the creation of an international satellite agency for monitoring, or via continuing advances in the capabilities of ‘national technical means of verification’.\(^{169}\)

• **EO for monitoring illegal activities, migration, etc**: EO-based geo-information services may be used to assess and address illegal activities and migration issues – e.g. the Waste Earth Observation Services (WEOS) project, which maps illegal waste disposal – to provide support to law enforcement and intelligence gathering.\(^{170}\)

• **Space-based enablers for emergency services**: EO, SATCOM and PNT and other future space products and services can contribute to strategy, planning, logistics, operations and other functions for terrestrial emergency services, including surveillance of incidents (e.g. protests, fires), communications in remote areas, and use of IoT devices, robotic and autonomous systems and other forms of emergency response.

• **Space-based enablers for aid and disaster relief**: Space services can support all phases of the disaster management cycle (e.g. prevention, preparedness, early warning, response and reconstruction).\(^{171}\) During the COVID-19 pandemic, for example, space-based assets have been used to monitor traffic at borders and improve flow of patients in hospitals.

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170 Morgan Stanley (2019b).
171 UNOOSA (n.d.a.), ESA (2020).
• **Planetary defence (detection and early warning):** Detecting Near Earth Objects (NEOs) using a variety of ground- and space-based telescopes, determining their orbits, and measuring their characteristics is an essential prerequisite to protect the Earth against devastating meteorite impacts.\(^{172}\)

• **Planetary defence (impact prevention):** This refers to deflection systems that are currently under development to prevent disastrous and potentially extinction-level NEO impacts on Earth. In future, this may benefit from spillover innovations from asteroid capture and mining (see Annex G on ‘Extractive industries’).\(^{173}\)

### Main actors

Defence, security and safety are inherently the concern of a wide variety of actors. This includes national governments and militaries (e.g. major military and nuclear powers, such as the United States, China, Russia, UK and France), international alliances and institutions (e.g. NATO, EU, UN)\(^{174}\), law enforcement, commercial organisations (e.g. defence manufacturers or cybersecurity specialists), civil society organisations, non-state actors (e.g. criminal groups, hackers, violent extremist organisations) and individual members of the public. Promoting a safe and secure space environment is also essential to prosperity and a wide array of scientific, commercial and other use cases for space out to 2050.

Besides the major nation-states, examples of commercial actors heavily involved in developing security-related capabilities in or enabled by space include: Boeing, Lockheed Martin, Northrop Grumman, Airbus Defence & Space, BAE Systems, Thales Alenia Space, QinetiQ, MDA/SSL, Orbital ATK, Iridium, Globalstar (communication systems), Space Life Origin (long-term secure data storage in space), Space Capital and Venrock (cybersecurity and secure communication). EO data-platform actors include Amazon, Atos, CloudEO, Google, DigitalGlobes and GeoCento.

### Value proposition to end users

| Government (civil) | • Support for law enforcement and emergency services in addressing criminality, disease, fires and other threats to life.  
| | • Support of EO for monitoring illegal activities and migration flows, encouraging legal and regulatory compliance.  
| | • Support of satellite-aided emergency beacon technology location services for search and rescue (SAR).  
| | • Support for disaster management (prevention, preparedness, early warning, response and reconstruction).  
| | • Support for resilience of critical national infrastructure. |

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172 Greenblatt & Anzaldua (2019); NASA (n.d.b).  
173 Greenblatt & Anzaldua (2019); NASA (n.d.b).  
174 North Atlantic Treaty Organisation (NATO); European Union (EU); United Nations (UN).
<table>
<thead>
<tr>
<th>Category</th>
<th>Benefits</th>
</tr>
</thead>
</table>
| Government (military) | • Benefits of control or use of space as the ‘ultimate high ground’, enabling global coverage and reach without topographical or other barriers found in other domains.  
                      • Support to SSA/SST in space to ensure a secure space environment for security, scientific and economic purposes.  
                      • Critical enabling capabilities for modern C4ISTAR and precision- and network-centric ways of warfare.  
                      • Critical enabling capabilities for multi-domain integration and coordination between joint and coalition forces.  
                      • Support for nuclear and conventional deterrence capabilities, missile defence and early warning.  
                      • Support for communications, intelligence and combat management/support, along with other defence functions.  
                      • Support to detection and deflection of space objects to prevent disastrous NEO impacts on Earth. |
| Civil (commercial)   | • More secure and stable environment in space, de-risking investments in other space markets (e.g. manufacturing).  
                      • Commercial benefits to industrial actors engaged in defence, security and safety sectors due to increased demand for assets in space.  
                      • Anticipation of loss and damage from early warning, and preparation for disasters and climate effects. |
| Civil (other)       | • Promotion of peaceful and collaborative use of space as a commons to benefit all humanity, encouraging global peace.  
                      • Support from EO and other services for civil society and NGOs to track migration issues and humanitarian disasters. |
| Consumers          | • Improved security and reliability for satellite-enabled services.  
                      • Anticipation of loss and damage from early warning and preparation for disasters and climate effects.  
                      • Potential for reduced threat to civilian populations from conflict, e.g. through deterrence or precision strikes. |
Estimate of timeframes

Defence, security and safety have been key considerations for space users since Sputnik I, if not before the launch of the first rockets and satellites. Today, many satellite technologies and services have their origin in military activity (e.g. the US Global Positioning System - GPS), or else are still employed – whether as government-only or commercial assets – in support of defence, security and safety functions.

Looking to the future, it is likely that improvements in SSA/SST capabilities and refinements in the capabilities of EO, SATCOM and PNT services will be important priorities for the 2020s and 2030s, providing ongoing support to terrestrial operations as well as contributing to a more secure space environment with better monitoring, as the number of objects and actors in space continues.

Many defence analysts suggest that the next major inter-state conflict (e.g. any conflict between the United States/NATO and Russia or China) may rapidly escalate towards confrontation in space (e.g. use of ASAT missiles or cyber and electronic attacks to target key nodes in space-based infrastructure) given the salience of the space domain to modern high-end warfighting. Others suggest that deterrence and peaceful coexistence can be maintained, even if conflict breaks out on Earth, due to mutual interest in avoiding an uncontrolled cascade of attacks, counter-attacks and collisions that could render entire orbits, especially in LEO, unsafe if not unusable.

More ambitious and paradigm-shifting developments, such as the positioning of large-scale military weapons platforms or bases in space, the maturation of planetary defence capabilities, or the creation of a verifiable ‘digital twin’ through pervasive EO, are likely to be realised further in the future, e.g. in the 2040s or beyond, if at all. Progress will depend also on the evolving security situation and the extent to which nations and other actors feel the need to invest in defence to deter each other, as opposed to building trust and peaceful collaboration through other political and technical means.

Drivers and enablers

Beyond the political and national security imperatives, there are several technical enablers for developing future space-based defense, security and safety applications.

Innovation is a key driver. For example, next generation SSA/SST can draw on advances in a range of related fields, such as satellite design, sensor technologies, processing power; Big Data, AI/ML and open source software. Similarly, advances in areas such as autonomy, robotics, smart materials, nanotechnology and quantum (whether for sensing, navigation, communications or computing) are opening new design options for equipment used as part of defence capabilities.

Another key enabler is the falling cost of access to space, due to a combination of technological advancement and commercialisation (e.g. through BlueOrigin, SpaceX and Virgin Galactic). This creates new mission types and tactical options for defence users, and enables a wider range of state and non-state actors to operate in space (bringing both benefits and challenges for security).

Finally, there is a strong consciousness among the international community to carry on activities in space on a peaceful basis in accordance with international law (e.g. the OST), and to build up a secure environment (e.g. the proposed Prevention of an Arms Race in Space (PAROS) treaty), though different stakeholders have differing perspectives on the best means for achieving this. This mutual interest may be an important driver for collaboration on topics such as SSA/SST in future.
Potential barriers and challenges to implementation

There are several important technical, political and legal barriers and challenges for implementation of future space-based defense, security and safety applications out to 2050:

- Democratisation of space increases the number of stakeholders who must be engaged in any collaborative effort to promote space security, with considerable risk that rogue states or commercial actors will act as ‘free riders’ or that space will face a ‘tragedy of the commons’.\(^{175}\)
- Divergence of national or commercial interests, or a lack of transparency and trust, may frustrate progress towards establishing new international treaties and norms governing space activities.\(^{176}\) For example, the EU’s attempt to promote a new Code of Conduct in 2008 has ultimately proved unsuccessful due to its inability to convince the current dominant space actor – the United States – or other major players, such as China and Russia, to agree on a common approach.\(^{177}\)
- National security is often cited as a justification for exemptions from international or national legislation, and defence issues are typically addressed through intergovernmental rather than supranational institutions, limiting efforts to enforce certain norms against nation-states’ wishes.
- The incentive for emerging powers or non-state actors to target space-based infrastructure is high and increasing, given the asymmetric reliance of the United States and others on satellite services.
- There are enduring technical, cost, cultural, political and legal barriers to implementing certain visions of future space-based capabilities, for example space-based interceptors for missile defence. New uses of space may prove technically infeasible, face challenges in promoting innovation with risk-averse military bureaucracies, or destabilise relations with other powers.
- The defence and aerospace sector also faces challenges relating to access to the necessary talent and skills, including for Science, Technology, Engineering and Maths (STEM).\(^{178}\)
- Governments face enduring pressure to allocate finite resources to other priority areas (e.g. health, education), potentially constraining the funding available to defence and security.
- There are strong ethical and political concerns about the militarisation of space, which may drive towards more peaceful uses, new forms of arms control, and updated space law.

Summary of potential impacts and implications for the space economy

<table>
<thead>
<tr>
<th>Prosperity</th>
<th>Economic benefits of enhanced defence, security and safety (i.e. prevention of damage to property or loss of life).</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Continued functioning of space-based assets and operations that are dependent on success of space security and debris management measures.</td>
</tr>
<tr>
<td></td>
<td>Support to law enforcement and regulatory compliance mechanisms, preventing corruption, theft and other crimes.</td>
</tr>
<tr>
<td></td>
<td>Support to cybersecurity, protecting commercial networks and data and preventing damaging breaches.</td>
</tr>
<tr>
<td></td>
<td>Spillover benefits from other dual-use security-related space technologies, e.g. advances in EO, SATCOM and PNT.</td>
</tr>
<tr>
<td></td>
<td>Commercial opportunities for relevant industries, most notably defence and security, aerospace, and cybersecurity.</td>
</tr>
</tbody>
</table>

\(^{175}\) Chaddha (2010).  
\(^{176}\) Lal et al. (2018).  
\(^{177}\) Su & Lixin (2014).  
\(^{178}\) Galai et al. (2020).
| Environment & net-zero economy | • Enabling safe operation of space-based infrastructure used for climate and environmental monitoring and protection.  
• Research for recycling orbital debris and reusability of space assets, reducing demand for terrestrial resources.  

| National security & defence | • Growing risk from orbital debris and man-made threats to space as a new form of Critical National Infrastructure.  
• Growing complexity of maintaining security and deterrence in the context of continuing democratisation of access to space.  
• Increasing requirement for defence organisations to secure access to and use of the space domain to protect both forces, infrastructure and populations in space and on Earth.  
• Increasing benefits but also risks associated with space-enabled C4ISTAR and network-centric warfare (e.g. risk of disruption by cyber or kinetic ASAT means).  
• Pressure on finite defence budgets to invest in space alongside other competing priorities in other domains.  
• Uncertain future of international law and norms around militarisation of space or use of certain technologies.  
• Uncertain future of space deterrence measures and of the balance of power in space given rising powers e.g. China.  

| Science & discovery | • Enabling safe operation of space-based infrastructure used for scientific, research and exploration missions.  
• Advance in techniques for SSA/SST, debris management and removal, and related technical disciplines (e.g. sensors).  
• Spillover benefits from other dual-use security-related space technologies e.g. advances in EO, SATCOM and PNT.  
• Advance in defence-funded research (e.g. new weapons).  

| International collaboration | • Potential for competition, confrontation and intentional or unintentional escalation to conflict in space (e.g. using ASAT capabilities, kinetic or non-kinetic).  
• Potential impetus to international collaboration in establishing governance, treaty law and norms for future use of space.  
• Potential impetus to international collaboration on issues of mutual interest e.g. SSA/SST, debris or planetary defence.  
• Potential catalyst to collaboration in other domains, including arms control mechanisms or trust- and transparency-building.  

179 Livne (2020).
## Annex F. Energy

### Energy

#### Definition

This cluster comprises all those activities in or enabled by space that are focused on generating, storing or transmitting energy (whether derived from fossil fuels, solar, wind, tidal, geothermal, hydroelectric, nuclear or other sources) to power machinery and provide heat, light and motion for human benefit.

#### Summary

The energy sector provides the basis for modern technology, society and economic functions, both on Earth and in space. Indeed, with regards to the potential future expansion of humanity into space, scientists have evaluated the level of a hypothetical civilisations’ technological and economic advancement based on the amount of energy it is able to harness for its purposes. The so-called Kardashev scale defines a Type I or planetary civilisation as one that is able to use and store all of the energy available on its planet; a Type II or stellar civilisation as being able to use and control energy at the level of its planetary system; and a Type III or galactic civilisation being able do so at the scale of its host galaxy. By astrophysicist Carl Sagan’s calculations, this leaves humanity currently as a Type 0.7 civilisation, meaning that significant advances are needed in energy production, storage and use if humans are to further develop the economy on Earth as well as expand to exploit other regions of the solar system.\(^{180}\)

At the same time, the growing challenges posed by climate change and environmental decline present a pressing need to invest in renewable energy sources, while political, security and economic concerns about reliance on foreign supplies (whether of oil, gas or key technologies such as civil nuclear) are also driving interest in innovative approaches to transforming energy markets, including through the use of space-based infrastructure, products and services.

Potential applications of space in the energy sector are wide-ranging and include direct benefits to both terrestrial and space markets. Improved EO, SATCOM and PNT services may, for example, improve the ability of governments and commercial actors to monitor and optimise power grids and services, as well as enable greater access to renewable energy and lower costs for consumers.

Apart from the provision of energy to power space exploration and human space habitats, space energy markets may also, according to some predictions, contribute to a ‘space industrial revolution’ by providing the energy needed for large-scale mining and manufacturing enterprises on orbit, the Moon or – one day – Mars.\(^{181}\) There are similarly ambitious plans in the United States, Europe, China, Russia and Japan to supply the growing terrestrial energy demands of the 2030s and 2040s through construction of space-based power stations, for instance using orbital solar panels or fusion generators.

However, complex technical requirements and economic challenges related to the high upfront costs of launching and assembling the necessary materials present important barriers to implementation.

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### Relevant use cases

<table>
<thead>
<tr>
<th>Space markets</th>
<th>Hybrid markets</th>
</tr>
</thead>
</table>
| • **Fuel cells and clean energy applications**: The extraction of H2O from polar ice caps on the Moon or Mars may support the implementation of hydrogen fuel cells to provide clean energy for space missions and human habitats.\(^{182}\)  
  • **Space-based energy storage**: Spacecraft, robotic systems, satellites and habitats may all be supported through advances in energy storage, e.g. battery farms to store energy from solar panels during the two-week-long lunar night.\(^{183}\)  
  • **Space-based mining and refining of propellant**: Asteroid or lunar mining and solar-generated electricity may be used to manufacture propellant in space (e.g. for rocket fuel or ion drives), increasing the range and duration of space missions and reducing launch costs for spacecraft from Earth.\(^{184}\)  
  • **Space-based refuelling infrastructure and services**: In conjunction with in-space propellant production, future applications may include refuelling infrastructure,\(^{185}\) e.g. refuelling waystations, robotic tankers and related services.\(^{186}\)  
| • **Orbital solar power**: Solar power represents a key space-based energy source given the relative lack of sunlight filtering through Earth’s atmosphere, and potential for continuous line of sight with the sun depending on the orbit used. Beyond use of solar panels to power spacecraft, future possibilities include establishing large orbital collectors to generate solar power in space and transmit it to terrestrial grids wirelessly through use of microwave transmitters or laser emitters.\(^{187}\) First proposed in 1968 by engineer Philip Glaser, technological advances could make this concept a reality by 2050.\(^{188}\)  
  • **Lunar solar power**: The Moon represents a favourable environment for large-area solar collectors due to the predictability and stability of solar flux to the lunar surface, the continuous solar exposure of the poles, and the lack of potentially disruptive weather or seismic activity.\(^{189}\) |

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182 Jucha (2016); Morgan Stanley (2019b).  
183 Schrunk et al. (2007).  
184 McInnes et al. (2019).  
185 Berger (2019).  
186 Cain (2019).  
188 Snowden (2019).  
189 Kalam (2008).
### Terrestrial markets

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| 
| 
| **Fusion power and Helium-3 mining:** The Moon may also provide a basis for progress in development of fusion energy, as the lunar surface is bombarded with Helium-3 from the solar wind. These isotopes offer a basis for cleaner, safer and affordable nuclear energy, given the lack of radioactivity.  
| **Solar weather monitoring for early warning and energy infrastructure protection:** Improved capabilities for monitoring and modelling space weather can not only provide early warning to space-based objects and personnel, but also play a vital role in protecting terrestrial energy grids against large-scale disruption due to geomagnetic storms caused by coronal mass ejections (e.g. the 1859 Carrington Event). |

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| 
| 
| **Modelling and prediction of market dynamics:** EO may be used to help monitor and predict energy supply and demand fluctuations. This includes resource monitoring (e.g. oil fields, gas etc.) as well as gathering data on indicators and drivers of fluctuating demand to inform AI-assisted models.  
| **Support to biofuels production to maximise yields for energy generation:** EO, SATCOM and PNT services may also be utilised in biomass monitoring, enabling biofuel production and energy production (see Annex A on use of space in precision agriculture techniques, including for biofuel).  
| **Remote monitoring of energy infrastructure:** EO, SATCOM and PNT services may be utilised in combination with other technologies (e.g. UAS) to provide remote monitoring of energy infrastructure, including offshore wind farms, power lines, pipelines and smart grid synchronisation. Weather prediction and monitoring services may also support the placing and maintenance of renewable energy installations. |

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190 ESA (n.d.c).
191 Los Alamos National Laboratory (2019).
192 Boyle (2020).
193 Werner (2017).
194 Catapult Satellite Applications (2017h).
195 Catapult Satellite Applications (2017a).
196 Werner (2017a).
Main actors

A variety of actors may be involved in implementation of future space-enabled services in terrestrial energy markets. This includes government regulators, manufacturers and energy suppliers (e.g. BP, EDF Energy and National Grid), as well as international stakeholders.197

Within the UK, ‘Energy’ and ‘Nuclear’ are also stated priorities of the Satellite Applications Catapult within its ‘Exploring New Markets’ focus area.198 At the European level, the ESA is actively developing a range of relevant programmes and capabilities, with some current examples including:

- ATMM (monitoring global coal stocks and flows);
- ERMS (EO, SATCOM and UAS in emergency response services for power grid operators);
- GridEyeS (for vegetation monitoring along power lines and wider risk modelling);
- MonICATO (using satellite-derived time measurement in power grids); and
- ThermCERT (identifying UK households who may qualify for support related to fuel poverty).

Looking beyond terrestrial markets, there is a range of actors and initiatives currently exploring the potential for space-based energy markets. Space agencies of the United States,199 China,200 Russia,201 Europe, India202 and Japan203 have all publicly announced interest in development of orbital solar farms. Commercial firms such as Northrop Grumman, SpaceX and SSL are also working independently or with NASA on techniques for orbital refuelling to reduce debris and extend satellite lifetimes.204

Military R&D organisations – such as DARPA and the US Naval Research Laboratory – have also expressed increasing interest in related research, including using the X-37B spaceplane for experiments in solar power transmission and exploring the potential of new forms of propulsion, e.g. nuclear thermal.205 Existing research highlights that US DoD funding has been crucial to-date in advances in the design and development of space solar power systems.206

Value proposition to end users

| Government (civil) | • Energy supplies for government-funded missions and installations in space and a reduction in launch costs. |
|                   | • Support in the protection of terrestrial energy infrastructure and optimisation of national energy markets. |
|                   | • Support for national investment decision-making in relation to funding energy systems infrastructure.207 |
|                   | • Support for fulfilment of UNFCCC emissions targets and national goals for increasing use of renewable energy. |
|                   | • Long-term energy security and reduced economic dependence on volatile energy markets (e.g. oil and gas). |

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197 Catapult Satellite Applications (2017h).
198 Catapult Satellite Applications (2020).
199 Mankins (2012).
200 Xinhua (2019).
201 Burgess (2018).
203 Sasaki (2014).
204 Burgess (2018).
205 Boyle (2020).
206 Mankins (2012).
207 Catapult Satellite Applications (2017h).
## Government (military)
- Provision of alternative energy sources for military applications, reducing reliance on imported fossil fuels.
- Supply of space-based energy to remote battlefield locations.
- Increased resilience of space and terrestrial CNI and energy systems against electromagnetic pulses.
- Potential for reducing environmental impact of defence to make contribution to wider government climate goals.

## Civil (commercial)
- Provision of energy for commercial space applications, including mining sites, factories and habitats.
- Commercial opportunities in new space energy markets, including orbital refuelling infrastructure and services.
- Increased efficiency and resilience of existing energy markets (e.g. through prediction of supply and demand fluctuations).
- Reduced personnel and maintenance costs for power grids through use of satellite-enabled remote monitoring.

## Civil (other)
- Support to scientific missions in outer space, as well as research into new power sources (e.g. fusion).
- Support to NGOs advocating a transition to renewables.

## Consumers
- Falling energy costs and more reliable power supplies.
- Benefits of reduced emissions and air and water pollution, leading to a healthier and more sustainable environment.

### Estimate of timeframes
Space products and services, including EO, SATCOM and PNT technologies, are already utilised in support of terrestrial energy markets, including in the monitoring of energy infrastructure. These can be expected to continue to mature out to 2030 and beyond, dependent in part on lead times for recapitalising outdated legacy systems (e.g. power plants, transmission lines) and the pace of change in replacing fossil fuels with renewable energy sources.

Estimated timeframes for some of the more novel and game-changing plans for space-based energy markets range from the near- to medium-term, given the complex technical requirements and the dependence on falling launch costs for viability. Several government and commercial organisations have already conducted initial orbital refuelling tests and have placed contracts to provide such services more routinely beginning in the early-to-mid 2020s. This may presage large-scale development of propellant manufacturing operations and refuelling waystations in orbit or around the Moon – and one day, Mars – as demand for long-distance spaceflight increases in the late 2020s, 2030s and 2040s.

In the field of space-based energy for terrestrial markets, the United States, China, Europe and Japan all hope to be able to build the first solar power stations in space between 2030 and 2040. For example, China has announced its aim to build a 200-tonne megawatt-level solar farm in orbit by 2035. The Japan Aerospace Exploration Agency is also working to a technology roadmap of ground and orbital demonstrations leading up to construction of a 1-gigawatt commercial power station in the 2030s.

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209 Werner (2017a).
210 Mankins (2012).
211 Ziesling (2019).
212 Burgess (2018).
213 Xinhua (2019).
214 Sasaki (2014).
Drivers and enablers

There are several non-technical and technical enablers for future development of space-based energy infrastructure and related services.

Commercial and policy incentives to support a transition towards cleaner and renewable energy sources (in line with UNFCCC emissions targets and national goals, e.g. the UK Government’s ambitions for a carbon net-zero economy by 2050) provide a powerful impetus for ongoing transformation in the terrestrial energy sector, whilst the democratisation and growing exploitation of space for a wide variety of purposes creates new demand and markets for energy generation, storage and refuelling.

The physical demands of launching objects into orbit or reaching escape velocity to journey further beyond Earth dictate a compelling business case for generating energy and propellant in space if the necessary technologies and techniques can first be perfected to a level where this becomes commercially sustainable. For example, continuing advances in space robotics are seen as an important enabler for orbital refuelling infrastructure and services, given the complex manoeuvres required to couple spacecraft and ensure safe transfer of propellant (e.g. cryogenic oxygen and hydrogen) without collisions, boil-off, leaks or other incidents.\(^{215}\) Proving the feasibility and benefits of orbital refuelling may also drive growing standardisation in satellite design to ensure space objects can be refuelled without requiring bespoke equipment.

Looking towards ambitious plans for space-based solar power stations, continuing investment in solar cells for terrestrial use is helping drive down costs and improve efficiency. Existing research indicates that ‘significant improvements in solar cell performance are envisioned’ in the near- 2020–2025 term (>33% efficiency) as well as 2025–2030 term (>37% efficiency).\(^{216}\) Additive manufacturing and innovative space-based manufacturing techniques may represent a potential solution to the cost barrier of building such megastructures, for example with use of solar-powered robotics that can ‘self-replicate’ in space using In-Situ Resource Utilisation (ISRU) from asteroid or lunar mining (see Annex G on ‘Extractive Industries’).\(^{217}\)

Potential barriers and challenges to implementation

The current cost of space launch represents a crucial barrier to the realisation of space-based energy markets, including orbital or lunar solar farms. Existing estimates of the costs for a ‘meaningful’ number of orbital solar power installations reaches, for example, many billions or even trillions of USD.\(^{218}\)

As described above, alternative techniques – including those utilising additive manufacturing to allow solar installations to ‘self-replicate’ in space – may address cost-related barriers. There are, however, significant technical barriers to the actualisation of such techniques in the near term. This includes, for example, enduring engineering challenges associated with the construction and operation of wireless power transmission systems that would be able to transmit solar power harnessed through lunar or orbital installations to the Earth’s surface safely (e.g. without posing a danger to birds, aircraft or human populations).\(^{219}\)

Furthermore, advances in renewable energy from terrestrial sources (e.g. ground-based solar cells, wind farms or tidal power generation) may diminish the incentives for humanity to look to outer space to sustain its intended transition towards renewable energy sources.

\(^{215}\) Stofan & Whitesides (2017).
\(^{216}\) Mankins (2012).
\(^{217}\) Fecht (2016).
\(^{218}\) Fecht (2016).
\(^{219}\) Fecht (2016).
## Summary of potential impacts and implications for the space economy

### Prosperity & innovation
- Energy supplies for spacecraft, habitats and other space infrastructure, enabling creation of new space-based markets.
- Increasing market opportunities for renewable energy and innovation in related technology areas.
- Increasing resilience of critical energy infrastructure and decreasing risk and costs of disruption.
- Falling energy costs to consumers and businesses.

### Environment & net-zero economy
- Support to transition to renewable energy sources (whether space-based or terrestrial) and fulfilment of UNFCCC targets.
- Support to development of new fuels for nuclear fusion e.g. Helium-3 isotopes from lunar mining, reducing toxic waste.
- Potential for space-based energy production to enable the long-term relocation of polluting industries into orbit.
- Support to optimisation of power grids to better align fluctuating supply with demand (e.g. accounting for day–night cycles for solar, weather for wind power and the tides).
- Incentivising investment in green technology as an enabler for a carbon net-zero economy.

### National security & defence
- Increasing need to secure space-based infrastructure as CNI to avoid cascading disruptions to terrestrial power grids.
- Improved capabilities for sustaining military operations in space through space-based refuelling.
- Improved energy security and less reliance on foreign sources of fuel (e.g. oil, gas) or technology (e.g. civil nuclear).
- Provision of alternative energy sources to address military needs, leading to more self-sustaining forces and a reduced logistics footprint (and associated force protection) for fuel.

### Science & discovery
- Enabling lower-cost and long-duration space exploration missions (e.g. via propellant manufacture and refuelling).
- Incentivising advances in scientific areas such as solar cells, robotics, batteries, supercapacitors and propulsion systems.
- Increasing availability and affordability of power supplies for energy-intensive research facilities and experiments.

### International collaboration
- Opportunities for development of common technical standards and regulation governing conduct of on-orbit refuelling.
- Opportunities for collaboration on space-based energy projects, e.g. multinational solar power stations.
- Opportunities for deepening collaboration on renewable energy projects and cross-border terrestrial energy markets.

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220 McInnes et al. (2019).
Annex G. Extractive industries

<table>
<thead>
<tr>
<th>Extractive industries</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition</strong></td>
</tr>
<tr>
<td>This cluster comprises all those activities in or enabled by space that are focused on extracting raw materials from the Earth or other celestial bodies (such as fuel, metals, minerals and aggregates) and processing these for subsequent use in industrial processes or by consumers.</td>
</tr>
<tr>
<td><strong>Summary</strong></td>
</tr>
<tr>
<td>Space-based extractive industries, particularly asteroid mining, are seen as one of the key macro trends supporting the future development of the space economy.(^{221}) Space-based in-situ resource extraction (ISRU) is widely considered a key enabler for long-term space missions, sustainable space habitats and wider space industrialisation, as well as a potential 'space industrial revolution'.(^{222}) Extracting key materials in space (e.g. oxygen, water, fuel, construction materials) would reduce or eliminate the reliance on launching supplies from Earth, bringing significant cost and time savings and enabling space-based installations to become more self-sustaining and resilient. In turn, extraction of space-based resources might bring transformative economic and environmental benefits to Earth. There are over 9,000 known asteroids close to Earth;(^{223}) and minerals deposited in the asteroid belt between Mars and Jupiter are estimated to be worth the equivalent of $100bn for every person on Earth.(^{224}) Capturing and mining a single asteroid could yield billions or even trillions of dollars’ worth of valuable resources such as helium-3, platinum, other precious metals, and rare earth minerals. For example, Asteroid 2011 UW158, which passed 1.5m miles from Earth in July 2015, is thought to include around $5 trillion of platinum.(^{225}) This has led to estimates that the sector could be responsible for creating the first trillionaires and a $100 trillion market,(^{226}) prompting comparisons to the explosive California gold rush of the mid-19th century and the development of various competing plans for future commercialisation.(^{227})</td>
</tr>
</tbody>
</table>

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221 Factories in Space (n.d.).  
222 Kalam (2008).  
223 Mining & Quarry World (2020).  
225 Goswami (2019).  
Beyond generating wealth, sourcing certain minerals and materials in space could reduce the need to extract finite resources on Earth and cut the pollution associated with heavy industry. This would bring environmental benefits and improve security of supply, for instance by reducing China’s dominance of the global supply base for rare earth minerals that are used in producing modern electronics. Further to ISRU or space-based mining, satellite technologies and services could support terrestrial extractive industries by providing connectivity for IIoT and EO-based monitoring.

While both space and terrestrial markets in extractive industries present extensive economic, as well as environmental, benefits, there are significant risks and barriers. These include regulatory and governance challenges – in light of the potentially drastic impact of extra-terrestrial mining for high-value materials in existing markets – as well as legal, security and safety issues associated with mining of space objects.

### Relevant use cases

<table>
<thead>
<tr>
<th>Space markets</th>
</tr>
</thead>
</table>
| **Asteroid mining**: Asteroid mining may include resource extraction for precious metals and water. This could subsequently be used for oxygen and hydrogen-based rocket fuel, forming a basis for space-based refuelling infrastructure.  
| **Comet mining**: Similar to asteroid mining, comet mining may entail the extraction of a range of resources, including volatiles and organics. As such, comet mining may contribute propellant and water-based propulsion systems for space operations and habitats.  
| **Lunar or Martian mining**: Initiatives on the Moon and Mars include extraction of water, helium-3, rare earth minerals and resources such as FeTiO₃ and TiO₂ (containing titanium), and other materials (e.g. regolith for construction purposes). Current prospects for lunar mining include propellant mining assisted by deployable solar arrays and radio frequency (RF), microwave and infrared radiation technology.  
| **Titan resource exploitation**: Saturn’s moon, Titan, is cited as a strong candidate for resource extraction, to include surface lakes of methane and liquid hydrocarbons as well as oxygen and water from below-surface ice reserves.  
| **Space biomining**: Extra-terrestrial biomining is a technique that utilises the growth of microbes in microgravity, stimulated by Martian gravity, to facilitate resource extraction by biological rather than robotic or mechanical means. Through biomining, in-situ materials such as regolith may be transformed into soils to support space-based agriculture.  
| **Recycling of space debris**: Space debris, including satellites, may be recycled and repurposed in-orbit for subsequent use in, for example, construction of new spacecraft or habitats. |

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Hybrid markets

- **ISRU (In-Situ Resource Utilisation):** ISRU captures the utilisation of in-situ raw materials in space operations include resource characterisation and mapping, production of mission consumables (e.g. propellants), engineering and construction (e.g. habitats), energy generation, storage and transfer, as well as manufacturing and repair (e.g. of robotic systems or solar panels) using in-situ resources. Advances in efficient and reliable ISRU techniques may also have potential utility in terrestrial construction and processed goods.

Terrestrial markets

- **EO for mining industry:** EO may provide support for terrestrial extractive industries, e.g. by monitoring ecosystems and resources, supporting operational efficiencies, and reducing environmental degradation through environmental baseline and monitoring in sites affected by mining operations.

- **Connectivity for mining IIoT:** Similar to other terrestrial industries, next-generation SATCOM and PNT technologies may provide connectivity for IIoT in the mining industry, enhancing automation, risk mitigation and productivity.

### Main actors

Commercial actors have been increasingly active in exploring the technical and commercial feasibility of space-based extractive industries, particularly asteroid mining, based on predictions for the industry to become ‘the gold rush of the 21st century’. Prominent commercial actors in extractive industries including the United States-based Planetary Resources and Deep Space Industries, as well as the UK-based Asteroid Mining Corporation.

Government agencies are also actively exploring the feasibility and safety and legal implications of space mining, along with the possibility of using resource extraction to directly benefit space missions (e.g. for building lunar or Martian colonies) or help generate revenue for government coffers. In the UK, ‘Extractive Industries’ is one of the designated focus areas of the Satellite Applications Catapult. In the United States, NASA’s own evolving concept for asteroid mining has included an ‘asteroid return’ operation, i.e. capturing and returning an asteroid to orbit around the Moon.

China has announced plans for both asteroid and lunar mining, including as part of its goal of establishing a permanent Moon settlement by 2035. The Chang’e-4 rover deployed to the Moon in 2019 was equipped with a ground-penetrating radar to search for subterranean resources such as iron ore, and ISRU is seen as a key enabler to a sustainable (and profitable) base on the Moon or other parts of the solar system.

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236 Greenblatt & Anzaldua (2019).
237 Blay (n.d.).
239 O’Connell (2019).
240 O’Connell (2019).
241 Blay (n.d.).
242 O’Connell (2019).
243 Goswami (2019).
Innovative smaller nations are also interested in capturing a share of this potentially transformative growth market, seeking to reconfigure their economies in a similar way to how oil and gas discoveries transformed the wealth of nations in Europe and the Middle East in the 20th century. Despite its small size and recent establishment of a national space agency in 2018, Luxembourg has become the first European country (and second in the world behind the United States) to adopt a legal framework securing property rights for resources harvested in space, and has provided R&D tax credits and other financial incentives to encourage commercial entities to base their space-mining operations in Luxembourg. Russia has previously sought to develop a framework agreement for partnering with Luxembourg on space mining, recognising the benefits of space resource extraction.

### Value proposition to end users

| **Government (civil)** | • Support for civil space operations through ISRU, enabling them to become more self-sustaining over long distances (e.g. by refuelling using ISRU) and long mission durations.  
| | • Reduced reliance on launching supplies from Earth, meaning fewer costs (financial and time) as well as reduced safety risk.  
| | • Potential revenue stream to benefit of government finances, transforming the budgets and profitability of space agencies. |
| **Government (military)** | • Reduced costs for military space missions due to ISRU.  
| | • Enhanced sustainability for military space assets even when resupply from Earth is compromised (e.g. during a conflict).  
| | • Enhanced space security through debris recycling, reducing the risk of cascading collisions and ‘the Kessler syndrome’.  
| | • Improved security of supply by reducing reliance on overseas terrestrial sources of critical materials e.g. rare earth minerals.  
| | • Technologies for asteroid capture, once proven, might be repurposed for planetary defence (or bombardment). |
| **Civil (commercial)** | • Extra-terrestrial resource extraction is estimated to represent a multi-trillion-dollar industry, offering direct economic benefits as well as supporting a broader ecosystem of support services and downstream applications (e.g. using mined materials).  
| | • Space-based services can enhance operational efficiency for terrestrial mining e.g. through use of IIoT.  
| | • Space-based services can support investment decision-making in terrestrial markets. |

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244 Brennan (2019).  
245 De Selding (2016).  
246 Soldatkin (2019).  
247 De Gouyon Matignon (2019).  
249 Blay (n.d.).
Civil (other)

- Support for the academic community through scientific research on extra-terrestrial resources.
- Support in development and advocacy of environmentally friendly and ethical terrestrial mining approaches. 250

Consumers

- Space-based technologies may help facilitate social engagement and reduce the detrimental local impacts of terrestrial mining, including encouraging compliance with environmental and ethical standards. 251

Estimate of timeframes

Current estimates indicate that the potential for some extra-terrestrial resource extraction activity (e.g. lunar) may be realised by the 2030s. This includes the establishment of resource mapping and measurements, the development of key technologies, and integration of ISRU into international mission architectures. 252 It may also include the capture of the first asteroid(s) to be brought safely closer to Earth for mining, with a possible near-term goal in the mid-2020s being to extract ice and sell it in space as propellant for other missions. 253

Similarly, China aims to capture and begin mining an asteroid by the end of the 2020s, as well as to move resource extractors, 3D printers and solar panels to the Moon to enable ISRU for construction of a lunar base that would be operable by 2035. Beijing then hopes to operate a self-sustaining and highly profitable ecosystem of mining and industrial outposts by 2045, positioning itself as a ‘world-leading’ space economy (and military and scientific superpower) before 2049, the 100-year anniversary of the People’s Republic of China. 254

Advocates of a ‘bootstrapping’ approach note that, while the first asteroid and lunar mining missions may not necessarily be profitable and will certainly need to overcome technical and other (e.g. legal) barriers, subsequent missions may become self-sustaining, with ISRU enabling space-based construction of new robotic systems that in turn enable more ISRU, and so on in a cycle of exponential growth. 255 Similarly, once an initial proof of concept has been achieved, it is possible a new ‘gold rush’ may ignite with rapid innovation and growth as new commercial and governmental actors race to reap the economic, political and military rewards of a share of the new space-mining market.

Critics observe that industry excitement and financial speculation about the prospects for imminent and highly profitable space mining proved premature in the 2010s, cautioning against another ‘bubble’. 256

Drivers and enablers

Only an estimated 4 per cent of asteroids in orbits proximate to the Earth could contain valuable metals, though others may have valuable deposits of water and other materials.

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250 Blay (n.d.).
251 Blay (n.d.).
252 European Space Agency (2019).
253 Abrahamian (2019).
254 Bedard (2019).
256 Abrahamian (2019).
A key enabler for ISRU, particularly the asteroid mining industry, is therefore determining, through other space-based assets, which asteroids should be mined for resources.\(^{257}\) The availability of sufficiently mature space robotics, sensors, resource processing systems, and AI/ML technologies as well as sustained investment are further key enablers for the realisation of ISRU\(^{258}\). The development of clear legal frameworks and clarity on property rights are also important drivers, and should influence both competition between commercial actors as well as between national governments seeking a lead in this emerging market.

Beyond space mining, the impact of satellite technologies and services on the terrestrial mining industry may be enabled by wider advances in adoption of Industry 4.0 and the technologies and processes associated with IIoT in the mining sector. This also includes the availability of advanced optical imagery and digital elevation models, as well as related AI- and ML-based techniques.\(^{259}\)

**Potential barriers and challenges to implementation**

There are extensive regulatory and legal challenges in relation to ISRU, including an immature and contested regulatory framework regarding property rights in space.

Among key scientific and technical challenges for ISRU are barriers associated with generating sufficient energy for mining techniques and processes; uncertainty about the composition and behaviours of asteroids/comets (especially once mining systems begin to land on their surface or attempt to redirect them towards Earth); and enduring challenges to operating robotic mining systems in such a complex and harsh environment.\(^{260}\)

The uncertain economic viability of early space-mining missions – as well as the potential economic impacts of space-based resource extraction on terrestrial markets – may be a further source of tension for governments and other commercial actors. Extensive mining for precious metals from asteroids may, for example, cause extensive shocks to existing markets, given the potential of sudden drastic increases in the supply of precious resources, such as gold or platinum.\(^{261}\)

Furthermore, there are important liability and safety concerns relating to the redirecting of any asteroids towards Earth, though advocates note that technologies used for doing so could also be used to correct the course of space objects heading for a collision with Earth (whether naturally occurring or thrown out of orbit by human activity).

**Summary of potential impacts and implications for the space economy**

<table>
<thead>
<tr>
<th>Prosperity</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Wealth creation through extraction and exploitation of resources sourced from space objects (asteroids, Moon etc.).</td>
</tr>
<tr>
<td>• Wider impact on innovation and productivity in other sectors as a result of reduced costs for raw materials.</td>
</tr>
<tr>
<td>• Reduced reliance on potentially unreliable terrestrial supply chains for critical resources e.g. rare earth minerals.</td>
</tr>
<tr>
<td>• Enabling growth of wider space economy and ecosystem, including space-based manufacturing and habitats.</td>
</tr>
</tbody>
</table>

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\(^{257}\) O’Connell (2019).

\(^{258}\) European Space Agency (2019).

\(^{259}\) Di Filippantonio (2020).

\(^{260}\) Sanders & Larson (2013).

\(^{261}\) O’Connell (2019).
| Environment & net-zero economy | • Enabling access to new energy sources to drive down energy costs for industrial processes and propellant for space flight.  
• Reducing reliance on launch from Earth, driving down costs for various space-enabled applications and markets.  
• Optimisation of terrestrial mining using space services to increase productivity and profitability. |
| Environment & net-zero economy | • Enabling space-based energy generation and transfer, using ISRU to reduce launch costs and provide basis for space-based manufacturing of solar panels.  
• Mining helium-3 as a source of future clean fusion energy.  
• Reducing environmental degradation produced by the terrestrial mining industry through use of IIoT for optimisation.  
• In the longer term, potential for space-based extractive industries to replace terrestrial mining, supporting de-industrialisation and conservation on Earth, shifting heavy industry off-planet. |
| National security & defence | • Self-sustaining military operations in space using ISRU.  
• Impact on security of supply for critical resources, including energy sources and rare earth minerals (e.g. from China).  
• Overlap between capabilities for asteroid capture and mining with those for planetary defence (or bombardment). |
| Science & discovery | • Support for scientific missions and deep space exploration by reducing launch costs and reliance on Earth re-supply.  
• Support for construction of large-scale research facilities on orbit, the Moon, Mars or elsewhere using ISRU.  
• Resources for new energy technologies e.g. fusion.  
• Incentivising investment in new sensors, robotics and other systems with wider application for exploration missions.  
• Advancing knowledge of space-based resources and objects, including asteroids, comets, the Moon and different planets. |
| International collaboration | • Resourcing of multinational space missions, using ISRU to ensure joint missions are more self-sustaining.  
• Incentives for international cooperation on space regulation, though some actors may seek to gain competitive advantage through state aid or by less robust standards on space mining (i.e. risks and challenges to the global level playing field).  
• Spillovers from asteroid mining into wider international cooperation on technical means for planetary defence. |
## Annex H. Finance and commerce

<table>
<thead>
<tr>
<th>Finance and commerce</th>
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<tbody>
<tr>
<td><strong>Definition</strong></td>
</tr>
<tr>
<td>This cluster comprises all those activities in or enabled by space that are focused on providing services involving the investment, lending and management of money and assets, including the trading of stocks, shares, commodities and property through global, national and local markets.</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Summary</strong></th>
</tr>
</thead>
</table>
| Advances in satellite technologies and falling launch costs are facilitating increasing awareness of and access to space-based services by financial and commercial actors. Services including EO, PNT and SATCOM are increasingly utilised by the financial sector for a range of applications: including trading algorithms, risk assessment, decision-making support, and precision analysis and optimisation of operations, processes and supply chains.  

Looking out to 2050, this trend is likely to intensify; with space products and services becoming even more integral to the function of global finance and trade; with new actors challenging existing market players with value propositions that exploit new technologies (i.e. FinTech) and draw on data, networks and infrastructure in space; and with both governments and commercial actors utilising space to help bring financial services to remote or developing parts of the globe (e.g. space-enabled connectivity for mobile/online banking).  

In turn, the convergence between the space economy and wider financial and technological innovations may bring transformations in how space actors finance and operate their businesses; for example, with trust services such as blockchain to enable ‘smart contracts’ for satellite operations. These advances could enable the development of a space-based sharing economy with distributed ownership of space assets and services, such as data and communications (i.e. a ‘gig economy’ for satellites). By enhancing trust, optimising pricing and matching supply and demand in real-time, such a space-based sharing economy could bring extensive benefits to public and private stakeholders.  

At the same time, complex technical, regulatory and governance challenges present significant barriers to its full realisation by 2050.262 |

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262 Stöcker (2017a).
Relevant use cases

**Space markets**
- **Trust and privacy services for space**: Blockchain may enable more secure satellite communications, including data processing and in-space data storage (e.g., enhancing cybersecurity for orbital server farms). Blockchain may also have wider utility in the space sector, including in relation to contracting and supply chain management.263

**Hybrid markets**
- **Access to space for Small and Medium Enterprises (SMEs)**: SMEs may benefit from space-based services, including access to satellite data, for purposes such as environmental monitoring.264 Equally, SMEs may increasingly participate in the space economy, including e.g. SME-owned smallsats.265
- **Blockchain-enabled satellite applications**: Blockchain-enabled satellite contracts, Next Generation Internet and data sharing services may enable more low-cost, distributed trust for satellite-enabled applications.266
- **Blockchain-enabled verifiable EO data**: Pervasive and verifiable EO may be used to generate trusted ‘digital twin’ of Earth (i.e. ‘ground truth’). Applications of such a service may include precision operations analytics to inform investments, agricultural monitoring for commodities trading, and climate and environmental risk monitoring, among others.267

**Terrestrial markets**
- **E-commerce and payments**: Future e-commerce and payments markets may be enabled by space technology and services such as dedicated satellites for e-commerce and ensuring secure transactions with next-generation SATCOM and PNT.268
- **Predictive analytics for finance and commerce**: Space-based services may be combined with AI/ML applications to analyse real-time and high-resolution imagery and identify economic patterns. This may contribute to better economic analyses, e.g. through analysing the future wealth of defined geographic areas (e.g. cities), anticipating demand for certain goods and services based on observed behaviours and trends (e.g. traffic flows), and modelling expected yields from different extractive industries (e.g. agriculture).269

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263 PwC (2019).
264 Edie Newsroom (2013).
265 Institution of Mechanical Engineers (2015).
266 Stöcker (2017b).
267 Stöcker (2017b).
268 China Daily (2016).
269 Tarr (2017).
• **Insurance and risk**: Space-based services may be used in combination with AI/ML techniques to provide advanced capabilities for the insurance and risk industry. This could include use of EO for catastrophic/risk modelling, event loss assessment and parametric modelling; and the application of SATCOM and PNT services to enable IoT and telematics, such as for driver- or usage-based insurance schemes.270

• **Investment decision-making**: EO and AI/ML may be used to inform investment decision-making, including through services such as impact-investment screening, monitoring and evaluation, and corporate and financial reporting.271

• **Optimisation of processes and value chains**: EO and AI/ML may also be used to optimise processes and value chains, including through automatic data processing, analysis and advanced decision support.272 This may in turn assist with monitoring regulatory compliance and conducting due diligence in support of mergers and acquisitions.

• **Connectivity for mass telecommuting**: Space-based technologies and services may contribute greater effectiveness in telecommuting, especially for multi-national organisations with vast data-sets and a global workforce in their business.

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**Main actors**

In 2020, an increasing number of industry stakeholders are engaging in space-enabled finance and commercial activities, most notably utilising SATCOM and PNT services, but also increasingly making use of EO in combination with nascent AI/ML capabilities.

A range of companies currently provide satellite-enabled services supporting investment decision-making, risk assessment and management, and optimisation of value chains and business processes.273 Out towards 2050, such services are likely to become more cost-efficient, higher fidelity in output and real-time in delivery, generating entirely new use cases as well as opening up a much broader customer base (e.g. selling to SMEs). In recognition of growth opportunities, Chinese e-commerce giant Alibaba has recently become the first commercial actor to launch a dedicated e-commerce satellite.274

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270 ESA (2012).
271 ESA (n.d.a.).
272 ESA (n.d.a.).
273 ESA (n.d.a.).
274 China Daily (2016).
In 2017, NASA awarded a grant to explore the potential for developing a blockchain-based spacecraft system\textsuperscript{275} (though initially to provide a basis for secure and resilient networking of NASA missions, not for financial purposes).\textsuperscript{276} Meanwhile, SpaceChain represents the first example of a community-based space platform aiming to build an open-source blockchain-based satellite network that would allow users to run decentralised applications in space for commercial or other reasons.\textsuperscript{277}

In the UK, the Satellite Finance Network is bringing together individuals and organisations from the finance, legal, insurance, government and space technology and applications communities to develop future space-enabled projects.\textsuperscript{278} ‘Financial Services’ is also one of the stated priorities for the Satellite Applications Catapult within its ‘Exploring New Markets’ focus area, with particular interest also in opportunities for convergence between space innovation, finance, international development and the environment as part of ‘Sustainable Finance’.\textsuperscript{279}

<table>
<thead>
<tr>
<th>Value proposition to end users</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Government (civil)</strong></td>
</tr>
<tr>
<td>• Monitoring real-time economic trends could facilitate development of better policy responses, industrial and land-use strategies, and fiscal and monetary interventions.</td>
</tr>
<tr>
<td>• Next-generation EO, PNT and SATCOM could all contribute to enhancing productivity and competitive advantage for digital economies, driving GDP growth and tax revenues.</td>
</tr>
<tr>
<td>• Supporting SMEs in their ambitions to access space may help to diversify economies and open up new domestic or export markets.</td>
</tr>
<tr>
<td><strong>Government (military)</strong></td>
</tr>
<tr>
<td>• Smart contracting and other tools may present new opportunities for public-private financing of space projects.</td>
</tr>
<tr>
<td>• Enhanced trust services may contribute to a more secure and resilient space industry and economy, reducing risks from cyber actors and serious and organised crime. (At the same time, increasing reliance on satellite-enabled services brings new threat vectors and challenges for protecting CNI.)</td>
</tr>
<tr>
<td><strong>Civil (commercial)</strong></td>
</tr>
<tr>
<td>• Improved risk assessment and mitigation capabilities.</td>
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<tr>
<td>• Using space-enabled analytics and modelling for investment decisions and optimisation of processes and value chains.</td>
</tr>
<tr>
<td><strong>Civil (other)</strong></td>
</tr>
<tr>
<td>• Space-based trust services may contribute to the development of a sharing economy in space. This would enable non-profit organisations and individual stakeholders to participate in distributed ownership of space-based assets and their products (e.g. data, manufacturing/mining outputs etc.).\textsuperscript{280}</td>
</tr>
</tbody>
</table>

\textsuperscript{275} Torky et al. (2020).
\textsuperscript{276} Wei (2017).
\textsuperscript{277} Spacechain (n.d.).
\textsuperscript{278} Satellite Finance Network (n.d.).
\textsuperscript{279} Hilton (n.d.).
\textsuperscript{280} Stöcker (2017b).
### Consumers

- Access to better goods through space-enabled e-commerce and access to novel financial products and services.\(^{281}\)
- Blockchain-enabled satellite applications may lead to new dynamics through which users, satellite owners and satellite systems themselves could dynamically create new services to pay for their launching, insurance, and other costs.\(^{282}\)
- Potential for space to generate ‘more accessible, faster and lower cost remote sensor data, as well as low-cost universal broadband communications for previously underserved areas and remote machines’.\(^{283}\)

### Estimate of timeframes

Many of the above-described use cases, including the use of EO in risk assessment and insurance, are already in early stages of adoption by industry stakeholders (as of 2020).\(^{284}\) Despite significant technical, regulatory and legal barriers, blockchain technology has also been of increasing interest to stakeholders within the space sector, particularly in supply chain management.\(^{285}\) It is likely that many of these novel approaches to utilising space to support finance and commerce will be mature by 2050.

### Drivers and enablers

The key enablers for finance and commercial markets in space are identified as significant and ongoing reductions in the cost of space launch and space-based technologies, particularly satellites.

Technological advances in satellite designs, including ‘smallsats’ and ‘nanosats’, as well as advances in space robotics contribute to greater accessibility of space for finance and commerce-related markets. Reducing cost is an especially important consideration for SMEs and new market entrants. Given EO, SATCOM and PNT services are already being used to varying degrees by financial actors, realising ambitions for next-generation services out to 2050 is likely to be driven by advances in satellite sensor capabilities (e.g. improved optics for real-time high-res video imagery, along with radar, lidar, etc.), improved satellite coverage (e.g. enabled by the creation of mega-constellations), improved connectivity and falling costs. The maturation of wider ICTs and Big Data technologies, along with AI/ML to automate the fusion and analysis of the data created by EO satellites and other sources, should also be a key determinant of progress.

Many of the more novel or ‘game-changing’ developments (e.g. a space-based sharing economy, including the distributed ownership of space objects, products and services) may be dependant more on shifts in organisational, commercial and regulatory models than on new technological breakthroughs. Key non-technical enablers include the development of new business models to ensure commercial sustainability.\(^{286}\)

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\(^{281}\) China Daily (2016).

\(^{282}\) Stöcker (2017b).

\(^{283}\) Stöcker (2017b).

\(^{284}\) ESA (2012).

\(^{285}\) PwC (2019).

\(^{286}\) ESA (2012).
Potential barriers and challenges to implementation

A key challenge for implementation of a sharing economy in space, enabled by technologies such as blockchain, is uncertainty concerning the ultimate impact and balance between benefits, cost and risk. While a space-sharing economy may improve social equity, justice and sustainability, some critics fear it may also result in ‘ever more paralysing levels of suspicion, division and resentment’. There are similarly concerns about the growing use of EO, networked IoT sensors and telematics to inform financial decisions that affect employees and consumers and undermine individual privacy and civil liberties. Some critics fear that the commercialisation of space may contribute to a ‘panopticon’ effect and the ongoing rise of ‘surveillance capitalism’. As such, there is a need to understand how different stakeholders within the public and private sectors will manage underlying issues of security, privacy and ownership within a space sharing economy or in the context of generation and transmission of vast data-sets through satellite networks. Additional uncertainty is derived from regulatory challenges as well as ambiguous legal frameworks, particularly surrounding blockchain technologies. In light of such uncertainty and potential governance challenges, some of the more ambitious applications within the space sharing economy paradigm – such as verifiable enhanced EO to create a ‘digital twin’ of the Earth – may currently face barriers of insufficient public acceptance.

Summary of potential impacts and implications for the space economy

<table>
<thead>
<tr>
<th>Prosperity</th>
</tr>
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<tbody>
<tr>
<td>• Improvements in financial investments, operations analysis and supply-chain and process optimisation may increase returns on investment from capital.</td>
</tr>
<tr>
<td>• Enhanced risk modelling and prediction may lead to reduced economic costs from climate change or other disasters.</td>
</tr>
<tr>
<td>• Better-informed government and regulatory bodies using space data and services may contribute to more effective fiscal, monetary and industrial policy interventions.</td>
</tr>
<tr>
<td>• Space-enabled connectivity may enhance the economic benefits of telecommuting, including through real estate, energy usage, reduced absenteeism, increased turnover and improved worker productivity. The economic benefits of telecommuting at the current average in the United States are predicted at $700bn a year.</td>
</tr>
</tbody>
</table>

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287 Stöcker (2017b).
289 PwC (2019).
290 Stöcker (2017b).
| Environment & net-zero economy | • Space-based trust services – including verifiable EO – may contribute to enhanced environmental monitoring.  
   • Space-enabled improvements in risk modelling in the insurance industry may enable companies and individuals to better understand, price and make investment or consumer decisions based on their environmental impact.  
   • The convergence between space, finance and climate may bring new commercial opportunities for green technology, and novel mechanisms for financing environmental projects. |
| National security & defence | • Services for space-enabled risk modelling and precision operations and behavioural analytics may be adapted from the financial sector for security and defence purposes (e.g. real-time terrorism or civil unrest risk assessments).  
   • Increased economic performance may contribute to enhanced fiscal resources for defence and security.  
   • Increasing reliance on space-enabled products and services entails a need to secure satellites, networks and related infrastructure against physical or cyberattack, with space a critical part of CNI in terms of economic security. |
| Science & discovery | • Increased economic performance may contribute to enhanced government and non-governmental resources for science.  
   • Smart contracting and other tools may present new opportunities for public-private financing of research projects. |
| International collaboration | • Shifting to a space-based sharing economy would enable radically reimagined governance and ownership of the space ecosystem out to 2050, with decentralisation and the potential for more user-centric collaboration and exploitation of satellites and space-based products and services.  
   • Smart contracting and other tools may present new opportunities for public-private financing of joint projects. |
Annex I. Health, pharmaceutical and medicine

Health, pharmaceuticals and medicine

Definition
This cluster comprises all those activities in or enabled by space that are focused on the prevention, diagnosis and treatment of illness or injury, contributing to the improved physical, mental and social well-being of individuals as well as the well-being of the population as a whole.

Summary
Space-based health and medical-assistance services represent an important enabler for future crewed space missions, including orbital space tourism, deep space exploration missions and lunar or Martian colonisation. This is due to the physiological challenges specifically associated with prolonged spaceflight, such as the effects of zero gravity, solar radiation and a gradual weakening of the immune system, as well as enduring generic risks such as physical injury or infection. Without gravity, controlling something as simple as a nosebleed presents a unique challenge. Delivering effective medical care to those travelling, working or living beyond Earth’s atmosphere will therefore be an important step towards spaceflight or settlement becoming safe, sustainable and popular.

Exploiting space may also provide opportunity for significant advances in medical science and services that benefit of terrestrial populations. This includes using space for medical and pharmaceutical research (e.g. microgravity experiments to develop therapeutic agents and vaccines), EO for real-time remote monitoring and modelling of future pandemics (e.g. through tracking population movements, behaviours and compliance with public health guidance), orbital manufacturing of high-value medical treatments or components (e.g. printing drugs or replacement human organs and tissue in zero gravity), and to deliver the next-generation connectivity required for large-scale uptake of telehealth and telemedicine services (e.g. monitoring of wearable sensors, remote consultations by video link, and remote surgery using robotic avatars). These developments could enable better quality and broader access to both health and social care on Earth and in space, as well as deliver other benefits – e.g. reducing absenteeism and boosting productivity in the economy.

To realise these ambitions out to 2050, several barriers must be overcome, including regulatory, legal and ethical challenges, and uncertainty concerning technology (e.g. the privacy implications of remote health monitoring), which may limit public acceptance and support from healthcare professionals.

292 Nawrat (2019).
293 Williams (2018).
294 Staedter (2019).
### Relevant use cases

<table>
<thead>
<tr>
<th>Space markets</th>
<th>Hybrid markets</th>
</tr>
</thead>
<tbody>
<tr>
<td>• <strong>Space-based health services</strong>: Medical assistance and health services may be provided through innovative techniques, such as 3D bioprinting of organs and skin tissue.(^{296})</td>
<td>• <strong>Space-based medical research</strong>: Future uses of space may include expanded medical studies, examining for example the health effects of radiation and microgravity. Space-based research may thus support advances in medical services and products with direct clinical applications both in space and on Earth (e.g. treatment and prevention of osteoarthritis), and leading to development of new therapies, vaccines and drugs.(^{300})</td>
</tr>
<tr>
<td>• <strong>Telehealth and telemedicine services for astronauts or orbital populations</strong>: Telehealth and telemedicine may play an increasingly important role in space missions, given the longer duration of missions and the potential for future permanent space habitats. Telemedicine and telehealth may therefore comprise preventive, diagnostic and therapeutic care, beyond emergency medical advice, enabled by communications links back to medical specialists on Earth.(^{297})</td>
<td>• <strong>Space-enabled applications for emergency medical and pandemic response</strong>: EO, SATCOM and PNT may be used to improve emergency medical and pandemic response, e.g. through using satellite communications for operations and utilising satellite data in delivering and distributing resources, as well as modelling possible spread of the epidemic.(^{301}) GNSS data may also be utilised in pandemic response through allowing individuals to observe social distancing or supporting use of UAS to deliver essential supplies.(^{302})</td>
</tr>
</tbody>
</table>

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\(^{296}\) Tangermann (2018b).  
\(^{297}\) Menon et al. (2017).  
\(^{298}\) Nawrat (2019).  
\(^{299}\) Sparrow (2020).  
\(^{300}\) Darling (2019).  
\(^{301}\) UK Government (2020a).  
\(^{302}\) UK Government (2020a).
Terrestrial markets

- **Space-enabled telehealth and telemedicine on Earth**: Space-based applications such as SATCOM and 5G/6G may enable telehealth and telemedicine services through access to broadband, including in remote areas, monitoring using wearables, or remote surgery using robotics.\(^{303}\) This may bring particular benefits to remote and isolated communities.\(^{304}\)

- **Space-enabled support and care to the elderly**: Space services may support elderly care through, for example, providing connectivity for environmental and physiological sensors, and other IoT devices used in smart home designs.\(^{305}\)

- **Connectivity for IIoT in pharmaceutical and medical equipment sectors**: Space-enabled IIoT connectivity may also improve processes and services provided by the pharmaceutical and medical equipment sectors, enhancing the efficiency, quality and speed of manufacturing in supply chains as well as the through-life support and maintenance of IoT kit in hospitals.\(^{306}\)

**Main actors**

Advances in space-based health, pharmaceuticals and medicine are supported by a range of public- and private-sector stakeholders, including private healthcare providers and civil space agencies. Government agencies also maintain sizeable programmes dedicated to space medicine: for example, the ESA’s Space Medicine Team comprises a dedicated group of medical doctors, biomedical engineers, exercise physiologists, psychologists, IT specialists, education coordinators, administrators and project managers working on these issues at the European Astronaut Centre.\(^{307}\)

In the UK, ‘Health and Wellbeing’ is also a priority focus area for the Satellite Applications Catapult, with sub-themes around ‘Emergency Response’, ‘Managing Long Term Conditions’, ‘Early Intervention and Diagnosis’ and ‘Remote Monitoring and Consultation’.\(^{308}\) This effort is supported by development of a new UK Health Living Lab at Westcott, co-designed by the Catapult and the National Health Service (NHS) Arden and Greater East Midlands.\(^{309}\)

The International Space Station has similarly been used as an orbital laboratory for health-related research since its inception, with experiments yielding a better understanding of issues such as trauma, ageing, disease and the environment. NASA cites ‘advances in telemedicine, disease models, psychological stress response systems, nutrition, cell behaviour and environmental health’ as examples of the benefits of previous space-based medical research to both astronaut and terrestrial populations.\(^{310}\)

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303 European Space Agency (2003).
304 Williams (2018).
305 Sumit et al. (2017).
306 Maktoubian & Ansari (2019).
307 ESA (n.d.b).
308 Vesey (n.d.).
309 Catapult Satellite Applications (2020f).
Examples of commercial operators active in this field include Techshot Inc., a specialist in microgravity research and manufacturing, and nScrypt, a manufacturer of industrial 3D printers, who have collectively developed a 3D BioFabrication Facility for use on the ISS.\textsuperscript{311} In telehealth and telemedicine, key players in the value chain include satellite operators and telecommunications companies, large ICT companies (e.g. Google, Microsoft, IBM), manufacturers of medical and monitoring devices, pharmaceutical companies (e.g. GlaxoSmithKline, AstraZenica), regulators, data security specialists and healthcare providers.

### Value proposition to end users

<table>
<thead>
<tr>
<th>Category</th>
<th>Value Proposition</th>
</tr>
</thead>
</table>
| **Government (civil)** | - Ability to support civil space missions, including long-duration exploration missions and orbital, lunar or Martian colonies, through provision of health and medical services.  
- Advances in space-enabled telehealth and telemedicine may improve the quality of and access to medical services on Earth and extend services to rural or remote areas (incl. in the Arctic, Antarctic and areas affected by natural disaster).\textsuperscript{312}  
- Increased resilience for terrestrial medical services (e.g. through ensuring connectivity and by using IoT to monitor and predictively repair medical equipment in hospitals).\textsuperscript{313}  
- Potential for reduced costs by improving efficiency of public healthcare systems (e.g. by using remote consultations).  
- Satellite data to inform public health interventions (e.g. EO for modelling pandemic risk and population behaviours). |
| **Government (military)** | - Advances in space-enabled healthcare could be utilised by the military both in space and on Earth, including to support telehealth and telemedicine for forces deployed overseas. |
| **Civil (commercial)** | - Economic opportunities for private sector healthcare providers, pharmaceutical companies and manufacturers of specialist medical equipment using insights gained through space-based research or space-enabled technologies. |
| **Civil (other)** | - Informing scientific research relevant to healthcare, pharmacology and medical sciences.  
- Support to civil society organisations and NGOs delivering education, outreach or medical support to communities affected by poverty, war or natural disaster (e.g. enabling operations for groups such as Médecins Sans Frontières).  
- Reduction in trauma incidents requiring treatment through improved workplace/transport health and safety, reducing the pressure on emergency departments. |

\textsuperscript{311} Glasure (2019).  
\textsuperscript{312} Lovett (2020).  
\textsuperscript{313} Maktoubian & Ansari (2019).
## Consumers

- Access to improved treatments, health and medical services based on scientific advances enabled by space-based medical research and space-enabled connectivity.
- Reduction in shortage of donor organs and wait-times for surgery (currently 4–5 months for a liver and 3 years for a kidney in the UK) by 3D printing necessary tissues in space.\(^{314}\)
- Improved support for elderly and social care in the community (e.g. through medical IoT, wearables, remote monitoring).

## Estimate of timeframes

Current advances in R&D indicate that space-based health services relying on additive manufacturing may be realised in the near term. In July 2019, the first 3D BioFabrication Facility was launched and installed on the ISS; by early 2020, it had been used to print human heart cells that were subsequently returned to Earth inside a SpaceX capsule.\(^{315}\) The ESA and University Hospital of Dresden Technical University in Germany have similarly begun producing skin and bone samples. Industry projections suggest that the market for 3D printing of organs could be worth $1.9bn by 2028, with scope for sizeable further growth thereafter as the technology matures, costs fall and uptake increases.\(^{316}\)

There are also existing case studies of telehealth and telemedicine being utilised in space, including for treatment of ISS crews, as well as use of SATCOM and PNT as the basis for remote health monitoring.\(^{317}\) The demands of the COVID-19 pandemic have accelerated the transition to telehealth and telemedicine; the global telemedicine market had been valued at $31.5bn in 2018 and is expected to grow at a Compound Annual Growth Rate (CAGR) of 19.28% to 2025,\(^{318}\) but COVID-19 has seen doctors now seeing between 50 and 175 times as many patients through telehealth as before.\(^{319}\) Projections for growth have subsequently been revised upwards, with telehealth potentially reaching $250bn in 2020.\(^{320}\)

Given that demographic change is expected to result in an ageing population and growth in healthcare spending to up to 30 per cent of GDP by 2050, there is significant and growing demand for space-enabled health applications as technologies mature.\(^{321}\)

## Drivers and enablers

As the use cases show, many space-based health services are likely to utilise additive manufacturing techniques, such as 3D bioprinting. Scientific and technical advances in additive manufacturing in general and – for microgravity specifically – are thus an important enabler of future space markets.

Advances in biological and medical sciences, e.g. development of stronger antimicrobial materials with increased stiffness, would also enable improvements in space-based health and medical services.\(^{322}\) Similarly, future advances in nanotechnology may also play an important role in improving medical services for humans in space, e.g. through the use of silicon nano-materials to target cancerous cells occurring due to the impacts of solar radiation.\(^{323}\)

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\(^{314}\) Yosra (2019).
\(^{315}\) Sparrow (2020).
\(^{316}\) Alexander (2019).
\(^{317}\) Lovett (2020).
\(^{318}\) Valuates Reports (2020).
\(^{319}\) Henry (2020).
\(^{320}\) ModernHealthcare.com (2020).
\(^{321}\) Fong (2015).
\(^{322}\) Nawrat (2019).
\(^{323}\) Jucha (2016).
Sustained high levels of demand for health, pharmaceuticals and medicine due to an ageing population on Earth and growing population in space out to 2050 are likely to provide a strong moral, social and economic logic for investment in this sector, and drive international collaboration to address common health-related challenges and goals.

**Potential barriers and challenges to implementation**

Space-based health services – such as bioprinting – to treat injuries face technical barriers due to the challenges produced by the condition of microgravity. Cost and lead times for delivery are also important considerations, though these may become less salient factors if the costs, flexibility and speed of access to and from space continue to fall.

Future applications of medical services such as telehealth and telemedicine may also be limited on interplanetary missions due to a delay in communications links. While this may currently represent a challenge, advances in AI/ML and autonomy may act as potential enablers for addressing such barriers, reducing reliance on real-time communications with a human.324

Future terrestrial markets – such as telehealth and telemedicine – may face a number of barriers, including the lack of common standards and relevant regulatory frameworks; limited availability, quality and speed of information transfer; concerns about privacy, ethics and data security; limited funding; and lack of public acceptance and political support at the national and international levels, which may disincentivise healthcare professionals from engaging in the provision of relevant services.325

At the same time, the COVID-19 pandemic has provided an unexpected and unprecedented impetus to rapid adoption of telehealth technologies by both the public and medical institutions, meaning that the ‘teething problems’ encountered may be more rapidly overcome.

**Summary of potential impacts and implications for the space economy**

| Prosperity | • Lowering cost of health and medical services, including telehealth and telemedicine.  
| | • Reduced pressure on public health and social care budgets, expected to be worth up to 30 per cent of GDP by 2050.  
| | • Reduced absenteeism due to illness, injury or disability, and increased workforce productivity.  
| | • Significant commercial opportunities and economic spillovers associated with new markets, e.g. telehealth and telemedicine.  
| | • Significant opportunities and economic spillovers associated with existing markets e.g. the large UK pharmaceutical sector. |
| Environment & net-zero economy | • Reducing carbon emissions and air pollution associated with travel for medical appointments or hospital care through encouraging telehealth. |
| National security & defence | • Improved health and medical services for defence personnel, including those deployed on operations in space or on Earth.  
| | • Reduced cost of health and medical services as a portion of defence personnel and operations budgets.  
| | • Improved responses to pandemics and CBRN326 incidents. |

324 Menon et al. (2017)
326 Chemical, Biological, Radiological, Nuclear (CBRN).
| Science & discovery | • Improved understanding of impacts of solar radiation and low gravity on human physiology.  
| | • Support for advances in terrestrial medicine – e.g. improvements in 3D bioprinting – which could be applied for conventional (terrestrial) medical treatments.\textsuperscript{327}  
| | • Development of new treatments, therapies and drugs.  
| | • Health and medical services in space enable safety for long-duration deep-space exploration missions and orbital, lunar or Martian colonisation.  
| | • Remote monitoring and analysis (using AI/ML) of vast data-sets from telehealth, delivering new insights into medical sciences and efficacy of public health interventions. |
| International collaboration | • Opportunities for international collaboration on joint medical research programmes in or enabled by space.  
| | • Opportunities for deepening and broadening cooperation between national health and social care systems, through ability to deliver remotecare across borders using telemedicine.  
| | • Opportunities for cooperation in setting new standards (e.g. on quality, safety, ethics, privacy and data security) for space medicine and space-enabled telehealth and telemedicine. |

\textsuperscript{327} Tangermann (2018b).
Annex J. Illicit activities

Illicit activities

<table>
<thead>
<tr>
<th>Definition</th>
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<tbody>
<tr>
<td>This cluster is distinct from the others, in that it does not focus on legitimate and lawful uses of space. Rather, it comprises all those activities in or enabled by space that are prohibited by national or international law, rules and customs.</td>
</tr>
<tr>
<td>Relation to other clusters: International treaties and national legislation on outer space continue to evolve, and different nations may permit or criminalise different acts. It is possible some use cases in other clusters may be legalised or de-criminalised in one jurisdiction, but punishable by law in another.</td>
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<table>
<thead>
<tr>
<th>Summary</th>
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<tbody>
<tr>
<td>The increasing scope of commercial activities in space and the growing reliance of many terrestrial markets on space infrastructure is increasing the potential for illicit or criminal activities associated with space. Currently, this primarily involves cyber or electronic attacks against satellites, networks and ground installations, but as space becomes an increasingly essential part of the wider global economy there is substantial scope for novel forms of criminality in – or enabled by – space out to 2050.</td>
</tr>
<tr>
<td>This includes illicit activities in space itself, including the potential for space piracy or space-based hacktivism to seize physical or cyber control of valuable space objects, or space-based forms of political and social protest and extortion (e.g. sabotaging a given nation’s or company’s satellites or space installations for ideological reasons, or to demand a ransom in return for a valuable space object or unlocking of its data – i.e. the ransomware model).</td>
</tr>
<tr>
<td>Though cyber and electronic attacks on satellites may create mostly temporary disruptions and damage – in contrast to physical attacks and close proximity missions to compromise a satellite or spacecraft – the potential frequency and impact of such attacks may significantly increase in the future as technologies advance and increasing numbers of non-state actors gain access to counter-space capabilities.</td>
</tr>
<tr>
<td>Satellites and other space objects might also be used in illicit ways that exploit disputed ‘grey areas’ and definitional or jurisdictional gaps in evolving national and international law on space. For example, disreputable businesses and criminal enterprises might flock to register their satellites and space vehicles with ‘flags of convenience’ issued by states with lax controls or a poor record of enforcing standards, sanctions or property rights in space.328</td>
</tr>
</tbody>
</table>

328 Kleinman (2011).
In turn, space infrastructure, products and services, such as next-generation EO, SATCOM and PNT, might be increasingly exploited for illicit and criminal purposes on Earth. This includes creating new revenue streams for criminal organisations as well as shaping the ways and means in which they seek to avoid detection, capture or prosecution by the authorities.

### Relevant use cases

| Space markets | • **Space piracy and criminality**: Space piracy includes malicious action against space crews or space-based assets for illicit purposes, such as extortion or theft. Space piracy represents a commercially motivated form of space-based illicit activity.  
| | • **Space-based protests and hacktivism**: Illicit activities in space may include hacktivism (hacking space-based systems for socially or politically motivated purposes) or other forms of political and social protest targeting nations or firms. |
| Hybrid markets | • **Cyberattacks on space objects, infrastructure and networks**: The proliferation of satellites and other space-based assets increases the potential vulnerability of space infrastructure and networks against cyberattacks, though the space sector is now beginning to recognise the cyber threat after failing to consider this issue in the design of earlier generations of satellite. Cyber vulnerabilities may result from the complexity of supply chains of space-based assets, as well as omission of patching, misconfiguration of systems, or other human errors.  
| | • **Electronic attacks on space objects**: Further to cyberattacks, space-based objects may also be subject to electronic attacks such as dazzling (the blinding of reconnaissance satellites with laser capabilities), jamming (creating ‘noise’ around RF bands to interfere with RF communications) and spoofing (production of a fake signal by a malicious device to downlink data from a satellite). While these actions may be conducted by state actors (e.g. as part of a military conflict), proliferation of relevant technologies to non-state actors opens up new threats e.g. of extortion. |
| Terrestrial markets | • **Use of satellite services and data for criminal purposes**: Satellite services and data may be misused for criminal purposes, including e.g. involving the use of secure SATCOM by criminal gangs, use of satellite-enabled UAS for smuggling narcotics and weapons, or compromising satellite-enabled IoT devices to steal personal data or intellectual property. |

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330 Horowitz et al. (2015).  
331 Holmes (n.d.).
Main actors

According to existing research, an increasing number of state and non-state actors have access to cyber and electronic ‘counter-space’ capabilities, and may be active or soon become active in some form of space-enabled illicit activities.332

Upstream industry actors – such as satellite manufacturers and operators – have been at the forefront of developing enhanced cybersecurity solutions for recent generations of space-based assets, as well as designing innovative techniques to further such future enhancements to the resilience of their systems against physical, cyber or electronic attack and subversion. Current solutions promoted by the industry include red-teaming cyberattack scenarios, enhanced cyber hygiene, supply chain and third-party governance solutions, and ‘improved understanding and appreciation of the cyber-physical security governance that needs to take place’ to protect current and future space-based systems.333

Governments, militaries and law enforcement also have an essential role to play, both in addressing outstanding questions of space law and implementing solutions to detect, counter and prosecute illicit and criminal acts associated with space.

Value proposition to end users

<table>
<thead>
<tr>
<th></th>
<th>Government (civil)</th>
<th>Government (military)</th>
<th>Civil (commercial)</th>
<th>Civil (other)</th>
<th>Consumers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Strengthening the regulatory and legal framework to address space-based illicit activities may have positive externalities, e.g. removing uncertainty about property rights in space.</td>
<td>• Further impetus to development of advanced SSA/SST capabilities to detect and monitor threats and illegal activity.</td>
<td>• Potential market opportunities for satellite cybersecurity, including e.g. smallsat cybersecurity solutions.</td>
<td>• Serious and organised crime may seek to profit from illicit activities by targeting high-value assets in space, or utilising satellite services for illicit purposes on Earth.</td>
<td>• Cyber risks to space infrastructure and networks may compromise data security and privacy. • Illicit activities in space may compromise reliable and secure delivery of space-dependent services on Earth.</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• Potential market opportunities for private security solutions to protect space-based facilities, spacecraft and ground sites.</td>
<td>• Protest movements, terrorists and hacktivists may seek to exploit space for high-profile public statements and attacks.</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• Potential market for security-risk management and insurance.</td>
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<td></td>
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</tbody>
</table>

332 Rajagopalan (2019).
333 Holmes (n.d.).
Estimate of timeframes

In 2019, NASA began investigating what may have been the first crime ever committed in space, when one of its astronauts was accused of illegally accessing her wife's bank account while aboard the International Space Station. This raised questions about what constitutes a crime in space and how to manage criminality beyond Earth’s atmosphere.

The 1967 Outer Space Treaty makes clear that nations should have legal responsibility over any space object (and associated personnel) on its registry while in outer space or on a celestial body. The Intergovernmental Agreement on Space Station Cooperation governing the multinational ISS makes clear that each nation has criminal jurisdiction over its own personnel onboard.334

However, legal issues and jurisdictional disputes are likely to become more complex in the near future as use of space shifts rapidly towards use of commercial vehicles and as disputes arise involving parties from multiple countries. ‘For instance, if someone from the US gets hurt on a private Japanese space hotel, along with other passengers from Spain and Singapore, it’s unclear exactly how to proceed’; multiple governments and agencies are likely to need to be involved.335

How quickly and in what forms – mundane or ambitious – future space-based criminality emerges will in part correspond to timeframes for realising government and commercial actors’ plans for expanding the legitimate uses of space out to 2050. For example, the most dramatic possibilities – such as space piracy – assume the availability of attractive targets (e.g. space tourism or asteroid mining operations) as well as low-cost launch options.

Drivers and enablers

A key driver for future space-based illicit markets is the increasing scope of activity in space, and the associated commercial value of such activities. The threat of space piracy has, for example, been primarily linked to the future of space mining and highly lucrative space extractive industries. Easier access to space is a further enabler for space-based piracy and other types of illicit activities.

The proliferation of space-based objects, particularly low-cost satellites and SmallSats, has also been a key enabler for exploiting cybersecurity vulnerabilities. In addition to the proliferation of IoT devices that extensively rely on satellite communications, the increasing number of satellites provides an increasing number of vulnerabilities and ‘entry points’ for malicious actors seeking to attack satellites through offensive cyber or electromagnetic means. Such vulnerabilities may also be easier to exploit given the frequent lack of cybersecurity protections of low-cost satellites.337

Uncertainties surrounding the regulation and legal framework governing space mining and extraction of resources in space may also incentivise malicious actors to engage in illicit space activities.338

335 Grush (2019).
336 Rajagopalan (2019).
337 Knott (n.d.).
Potential barriers and challenges to implementation

Despite the significant challenges associated with countering space-based illicit activities, there are potential avenues for strengthening satellite cybersecurity and other responses to this threat. Current advances with modulation and encryption technologies may, for example, enable better protections for LEO satellites. Technological advances in AI/ML techniques may also enable satellite operators to detect potential attacks on satellites earlier, facilitating more timely responses. Blockchain and trust-enhancing technologies also provide new mechanisms for better securing and monitoring supply chains within the space sector, as well as the exchange of data between space objects and with ground stations.

Collaboration between different industry stakeholders (including the satellite and cybersecurity industries), the civil space sector and military agencies may also facilitate the recognition of lessons learned and further improvement in response strategies.

Summary of potential impacts and implications for the space economy

<table>
<thead>
<tr>
<th>Category</th>
<th>Impacts and Implications</th>
</tr>
</thead>
</table>
| Prosperity                    | • Threats to legitimate space operations and property rights, with criminal activity imposing additional security costs on lawful space users and threatening economic returns.  
  • Potential for uncovering and addressing supply chain vulnerabilities of space-based objects, and thus improving value-for-money on initial investment. |
| Environment & net-zero economy| • Increasing incentive for polluting governments, businesses and criminals to destroy or falsify EO data used to monitor compliance with climate and environmental regulations.  
  • Threats to space objects used to support the green economy. |
| National security & defence    | • Development of improved cyber defence capabilities and improvement of cyber resilience for space infrastructure.  
  • Potential strengthening of stakeholder collaboration on SSA/SST, space security, cybersecurity and related matters. |
| Science & discovery           | • Advances in academic research on cybercrime and socio-economic dynamics of crime in outer space.                                                                                                                     |
| International collaboration    | • Potential for strengthened international collaboration to counter space-based threats and illicit activities.  
  • Potential for strengthened international collaboration on international space law and regulatory matters.  
  • Enduring risk of certain nations creating a more permissive legal environment for space criminals for their own profit (i.e. space-faring ‘flags of convenience’), allowing illicit activity to fall outside of transnational cooperation frameworks on outer space. |

339 Holmes (n.d.).
Annex K. Logistics

**Logistics**

**Definition**

This cluster comprises all those activities in or enabled by space that are focused on the integration of storage, transportation, cataloguing, handling and packaging of goods, and organising supply chains to enable the efficient flow of resources between their point of origin and point of consumption.

Relation to other clusters: For future space applications relating to the narrower task of moving people and goods from one location to another, see Annex O on ‘Transport’.

**Summary**

The future of logistics to 2050 encompasses both complex space-based as well as terrestrial processes directed at the transportation of goods and equipment. This is a key enabler for sustaining human life in orbit, as well as ensuring the efficient functioning of agricultural, energy, manufacturing and other supply chains in space or on Earth. The terrestrial logistics sector currently accounts for around 14 per cent of European GDP and is expected to grow to up to 40 per cent by 2040.341

Future space missions and habitats are likely to be accompanied by the emergence, or further development, of specialist commercial logistics services for space including orbital, lunar and Mars re-supply missions, as well as material recycling services. Future space-based services – such as improved EO, PNT and SATCOM – may also be used to support supply-demand optimisation and further advances in Just-In-Time (JIT) logistics, Indoor Positioning and Navigation (IPIN), smart ports and infrastructure, and the use of autonomous vehicles as delivery systems – all services that may in future be realised in space as well as for markets on Earth.

Lastly, future integrated logistics systems may be enabled by next-generation space-based services, including satellite-enabled global 5G/6G connectivity. Though the increasing connectivity and proliferation of IoT technologies in the logistics industry may encourage and enable greater utilisation of space-based services, there remain several technical, regulatory, security and usability challenges that may present barriers to rapid adoption between now and 2050.

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341 Cefriel (2019).
### Relevant use cases

#### Space markets

- **Closed-loop ecosystems, material recycling and in-situ resource utilization (ISRU):** ISRU may include space-based logistics and material recycling services – such as recycling of plastics, aluminium, steel and other structural materials – and AI-enabled optimisation of resource supply and demand in closed loops.\(^{342}\)

- **Commercial orbital re-supply services (CRS):** Orbital CRS may be used to transport crew supplies, vehicle hardware, materials for scientific experiments and new satellites (e.g. cube-sats), in support of existing orbital missions.\(^{343}\)

- **Commercial lunar re-supply services:** Future logistics markets may also include CRS for crewed or uncrewed lunar colonies, including e.g. NASA's Lunar Gateway outpost.\(^{344}\)

- **Commercial Mars re-supply services:** Future space missions may include the operation of crewed and robotic missions, as well as cargo launch services to and from the Mars surface.\(^{345}\)

#### Hybrid markets

- **Connectivity for IoT for supply-demand optimisation and Just-in-Time (JIT) logistics:** Logistics management has made increasing use of IoT applications, including for supply-demand optimisation, remote vehicle and cargo monitoring, and facilitating JIT logistics using satellite communications.\(^{346}\)

- **EO for supply-demand optimisation and JIT logistics:** Supply-demand optimisation and JIT logistics may also benefit from EO data, which may be used to monitor global supply chains (e.g. ground, shipping and port activity) and demand trends.\(^{347}\)

- **Satellite-enabled Indoor Positioning and Navigation (IPIN):** IPIN services are enabled by GNSS satellites and include asset and staff tracking, location-based services and geofencing. This may be used in logistics operations by various industries, particularly in complex (space-based as well as terrestrial) facilities, such as factories and warehouses.\(^{348}\)

- **Satellite-enabled smart ports and infrastructure:** Space-based services may provide EO, PNT and SATCOM for next-generation ‘smart ports’ and other space and terrestrial infrastructure, integrating AI, Big Data, IoT and blockchain technologies as enablers for performance optimisation.\(^{349}\)

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\(^{342}\) Greenblatt & Anzaldua (2019).

\(^{343}\) Foust (2017).

\(^{344}\) Gebhardt (2019).

\(^{345}\) NASA Office of the Chief Technologist (2014).

\(^{346}\) Morgan Stanley (2019b).

\(^{347}\) Morgan Stanley (2019b).

\(^{348}\) Catapult Satellite Applications (2017n).

\(^{349}\) Natalucci (2019).
### Satellite-enabled autonomous vehicles as delivery systems

PNT and SATCOM services may facilitate the operation of robotic and autonomous vehicles as delivery systems, including supporting vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication and swarming.  

### Next-generation connectivity for integrated logistics systems

Terrestrial markets may include space-enabled integrated logistics systems, integrating IoT and satellite data.

### Next-generation PNT for integrated logistics systems

GNSS may support advanced logistics systems including through cargo, vehicle and worker tracking and monitoring services.

### Main actors

Today, NASA’s CRS programme – the Commercial Orbital Transportation Services programme – contracts with two commercial providers for orbital CRS, namely SpaceX and Northrop Grumman (previously Orbital ATK). A third supplier, Sierra Nevada Corporation, will be added through the CRS-2 contract. Commercial providers have also been increasingly active in space-based recycling services. An example of this is the Commercial Polymer Recycling System (CPRS) being developed by orbital manufacturing specialist Made in Space.

On Earth, an extensive range of stakeholders operate within the terrestrial logistics market and intersect at different points in the value chain. This includes UK-based developers and service providers who may increasingly utilise space-based services.

The current market for satellite-enabled IPIN services includes several UK-based providers with a potentially strong position in the global market. These include: Focal Point Positioning, currently developing advanced satellite positioning capabilities for indoor areas and urban environments; Faltech GP355S, focusing on GPS repeater technology to provide GPS coverage for buildings and structures; and Sensewhere Ltd, which is developing IPIN for use in urban areas.

### Value proposition to end users

- Commercialisation of space logistics, particularly CRS, may enable civil space agencies to focus finite resources on other activities (e.g. R&D and scientific advancement).
- Greater resilience of civil space missions by ensuring affordable and robust provision of CRS.
- Enabling sustainable space-based ecosystems and value chains, including habitats, orbital factories and mining.
<table>
<thead>
<tr>
<th>Segment</th>
<th>Advancements</th>
</tr>
</thead>
</table>
| **Government (military)** | • Advancements in logistics in space and on Earth to improve support and sustainment of deployed forces in all domains.  
• Improvements in resilience and cost-efficiency of logistics provision, including for operations in austere environments.  
• Enabling greater use of autonomous systems for logistics, reducing force-protection requirements and risk to life. |
| **Civil (commercial)** | • Commercial space launch and transport market opportunities, including long-duration missions.  
• Optimisation of business and logistics processes for both space-based and terrestrial operations.  
• Supply-demand optimisation may increase productivity and make more efficient use of capital and labour.  
• Enabling greater use of autonomous systems for logistics, improving efficiency and reducing wage costs. |
| **Civil (other)** | • Monitoring and optimising logistics systems and fleets to reduce carbon emissions and air pollution.  
• Enabling civil society and NGOs to deliver aid and supplies to communities in remote locations or during natural disasters. |
| **Consumers** | • Integrated terrestrial logistics processes, opening new possibilities in terms of global trade, e-commerce and retail.  
• Increased quality and affordability of products through JIT manufacturing and logistics to maximise cost-efficiency.  
• Rapid delivery of high-value and perishable items, e.g. medical treatments delivered to the home. |

**Estimate of timeframes**

Different segments of space-based and space-enabled logistics markets are currently in different stages of development.

Commercial re-supply flights to the ISS are already being operated by NASA and its commercial partners. Though CRS missions to lunar and Martian outposts are yet to be realised – given the lack of any such settlements to generate demand – SpaceX’s future plans currently include the provision of crew and cargo launch services to Mars in the 2030s.358 Other commercial logistics services, including in-space material recycling, are currently under development.359

Terrestrial markets for space-enabled applications in logistics (e.g. use of IoT) are growing, with significant development in relevant markets projected by 2030 and maturing by the 2040s.360

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**Drivers and enablers**

Commercial re-supply markets are first and foremost enabled by efforts to optimise space operations through commercialisation, and the accompanying changes in regulatory contexts and funding programmes for CRS. Current advances in orbital CRS, which may constitute enablers for future growth of the market, include the ability of missions to carry more cargo through increased pressurised volume, carry ‘time-sensitive’ cargo (e.g. biological experiments), remain longer docked to the ISS or other space station, and perform long-duration missions.361

Technological advances in propulsion and other relevant technologies may also enable advances in CRS, including lunar and Mars re-supply services. This includes e.g. solar electric propulsion and improvements in ion engines, which may be used by future commercial re-supply missions.362

The future growth and development of space-based terrestrial logistics markets may be enabled by continued technological advancements (e.g. in AI/ML, sensors, autonomy and ICTs) and the proliferation of smallsats and LEO constellations. The proliferation of space-enabled IoT applications in the logistics industry, as well as increased usage of technologies such as smartphones with location/navigation sensors, may also incentivise further market growth and development of space-enabled logistics services, such as IPIN.363

**Potential barriers and challenges to implementation**

Barriers to CRS in space include the need for adequate demand (e.g. from space-based settlements, factories etc.) to make certain missions commercially viable and encourage innovation and new market entrants; regulatory issues (e.g. around licensing, liability); and concerns about safety and debris.

Several barriers currently exist for the adoption of space-based applications in terrestrial logistics markets. These include the initial costs of transforming legacy systems to adopt new space-enabled technologies, the lack of accuracy and insufficient coverage of existing PNT solutions, as well as limited connectivity for services such as IPIN. Such challenges with performance of the technology may limit incentives for end users and consumers, in addition to potentially increasing the risks from identity theft, limited usability, cyberattack and insufficient data-security protections.364

Future trends in the logistics market will also be subject to wider developments in the global economy, particularly the scale, complexity and international or local character of supply chains (e.g. driven by the impact of emerging economies and of trends such as re-shoring, economic protectionism or globalisation).365

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361 Foust (2017).
363 Catapult Satellite Applications (2017n).
364 Catapult Satellite Applications (2017n).
365 Deutsche Post (2012).
### Summary of potential impacts and implications for the space economy

| Prosperity | • Facilitating market opportunities for NewSpace markets in orbital and other space re-supply logistics.  
| Environment & net-zero economy | • Optimisation of logistics leading to a reduction of environmental impact from the sector.  
| National security & defence | • Advances in space-enabled military logistics to support deployed military forces in all domains.  
| Science & discovery | • Commercial re-supply services provide support for scientific missions and deep-space operations. They may also enable space agencies to focus resources on scientific and R&D activities, facilitating advances in science & discovery.  
| International collaboration | • Increased resilience of re-supply for international space exploration and exploitation missions.  
| | • Potential for deepening of integration between national economies (both on Earth and in space), encouraging commercial and regulatory cooperation.

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366 Catapult Satellite Applications (2017n).
Manufacturing

Definition
This cluster comprises all those activities in or enabled by space that are focused on the transformation of goods, materials or substances into new finished products through a mix of design, fabrication, processing and assembly using labour, machines, tools and chemical or biological processes.

Relation to other clusters: For those future space applications relating to the extraction of raw materials to enable subsequent manufacturing activities, see Annex G on ‘Extractive industries’.

Summary
Manufacturing represents a major share of the global economy and trade, providing the finished products used in a wide range of contexts and activities (e.g. from aircraft and cars to industrial equipment or consumer goods).

Though the UK economy has shifted towards a greater emphasis on services (e.g. finance, retail) in recent decades, official statistics for 2018 show that manufacturing in the UK accounted for 10 per cent of Gross Value Added (£191bn), 8 per cent of jobs (2.7m), 42 per cent of exports (£275bn) and 65 per cent of R&D spending (£16bn). Rhodes (2020) Aerospace, including the UK space sector as well as defence and civil aviation, represents an important part within this. Several other major economies have larger manufacturing sectors in absolute terms or as a share of GDP, for example including South Korea (30 per cent), China (29 per cent), Germany (23 per cent) or Japan (21 per cent). Rhodes (2020) However, the UK Government has made clear its intention to support the development of high-value manufacturing, including as part of the ‘levelling up’ agenda to increase economic opportunity in all regions and parts of the UK.

The growing use of space offers prospects for an array of new innovations and applications in the manufacturing sector, both for space-based and terrestrial markets. The launch of increasing numbers of spacecraft and satellites entails the potential for sustained growth in demand for the upstream segment of the space economy, i.e. companies involved in the design and manufacture of spacecraft, satellites (incl. smallsats) and payloads (e.g. sensors, antennae, power systems etc.).

367 Rhodes (2020).
368 Rhodes (2020).
369 Skidmore (2020).
Looking out towards 2050, there is also a growing market for manufacturing in space itself. Examples could include, in the near term: on-orbit or lunar manufacturing and assembly, additive manufacturing and microgravity manufacturing. While the initial focus may be on niche markets and high value products (e.g. replacement organs printed in zero gravity, or replacement parts made in orbit to reduce the need for resupply missions launched from Earth), proponents hope one day to be able to move large-scale manufacturing activities. This industrialisation of space would support development of the wider space-based economy (e.g. habitats, mining enterprises) as well as enabling de-industrialisation of the Earth to reduce the impact of pollution and carbon emissions on the climate and environment.

Space-based applications may also bring significant benefits to terrestrial manufacturing, for example through advances in satellite-enabled connectivity and PNT services to support implementation of the industrial Internet of Things (IIoT) and realisation of a Fourth Industrial Revolution (Industry 4.0). This would focus on use of networked systems, industrial robotics, AI/ML, additive manufacturing techniques and cyber-physical systems to transform traditional manufacturing and increase productivity.

However, technical challenges exist for on-orbit manufacturing, and the types of object that can be created in space may be limited due to diverse technical requirements, as well as cost considerations. Similarly, uptake of space-enabled IIoT and Industry 4.0 technologies is dependent on overcoming barriers to innovation in the manufacturing sector, including cost and cybersecurity concerns.

### Relevant use cases

**Space markets**

- **On-orbit, lunar or Martian manufacturing**: Space-based manufacturing may allow fabrication of components, parts and products to meet demand from space markets (e.g. to enable long-duration missions or establishment of habitats). To minimise reliance on costly launches from Earth, this could include use of in-situ resource utilisation (ISRU) to extract raw materials from asteroids or the lunar surface to feed industrial processes (e.g. 3D printing) to produce products locally (e.g. building new solar panels or robotic systems in-situ).

- **On-orbit, lunar or Martian assembly**: Space-based assembly could provide the mean to assemble diverse objects in space such as spacecraft or satellites, enabling launched them into space from Earth disassembled to save space within the rocket or launch vehicle, or combining specialist components built on Earth with other parts made in space.

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370 The Manufacturer & Oracle (2020).
371 O’Connell (2019).
372 Boyd et al. (2017).
### Hybrid markets

- **On-orbit metal manufacturing**: Space-based metal manufacturing could be used to produce stronger and more durable, rigid conductive components or reflective surfaces.\(^{373}\)
- **Microgravity manufacturing**: Some materials can only – or most easily – be fabricated in the microgravity environment of space, and are highly valued on Earth.\(^{374}\) For example: fibre optic materials, industrial crystallisation, super alloy casting, human stem cells, and ceramic stereolithography.\(^{375}\)
- **Additive manufacturing**: Often referred to as 3D printing (just one example of an additive technique), this method could help to build products in space by using a printer to build up layers of material. This entails new design options and less waste compared to subtractive manufacturing.\(^{376}\)

### Terrestrial markets

- **Connectivity for Industrial Internet of Things**: Future SATCOM (see Annex N on ‘Telecommunications’) may lower costs and improve performance for IIoT devices, enabling real-time monitoring and optimisation of manufacturing processes.\(^{377}\)
- **PNT services for Industrial Internet of Things**: New satellite technologies may support advances in Indoor Positioning and Navigation (IPIN), e.g. for machines, robotics, parts and workers within factories, warehouses or supply chains.\(^{378}\)

### Main actors

A wide variety of actors, large and small, are already involved in the space manufacturing sector, contributing to value chains that produce spacecraft, rockets, satellites and payloads. Beyond space, the global manufacturing sector is comprised of a mix of state-owned enterprises, private companies, large multinationals or industrial conglomerates, and small and medium enterprises involved in complex supply chains and different markets (e.g. automotive, electronics).

Governments also play an important role both as customers as well as regulators, including through setting industrial strategy and policy. Major global players include China, the United States, Japan, South Korea, India, Germany and other European nations (including France, the UK).

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373 Werner (2017b).
375 Greenblatt & Anzaldua (2019).
376 Ghidini (2016).
377 Mohney (2020).
378 Mohney (2020).
Looking to the future development of space-based manufacturing to 2050, several government and commercial organisations have been prominent in exploring relevant initiatives. This includes both civil and defence research agencies (i.e. NASA, ESA and DARPA). In the United States, for example, NASA recognises that future long-duration space missions ‘require a paradigm shift in the design and manufacturing of space architectures’, necessitating investment in the In-Space Manufacturing (ISM) programme led by the Space Technology Mission Directorate. The Agency has also been involved in multinational collaboration on the ISS, which has hosted experiments relating to orbital 3D printing and related technical challenges. In the UK, Catapult Satellite Applications has organised events and initiatives on the issue of manufacturing for and in space.

The decade since 2010 has also seen the emergence of specialist companies, such as Made In Space, Inc., which focuses on development of 3D printers for use in microgravity and has partnered with NASA to supply them to the ISS. Other firms active in emerging space-based markets or the use of space technologies to support the terrestrial sector include: Tethers Unlimited, the Interlog Corporation, Techshot Inc, Space Systems Loral, Orbital ATK, Arianegroup, Blue Origin, SpaceX, Rocket Lab, Thales Alenia and Iridium (IoT Satellites).

<table>
<thead>
<tr>
<th>Value proposition to end users</th>
<th>Government (civil)</th>
<th>Government (military)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Support to government industrial strategy and priorities for supporting high value manufacturing (exports, jobs, IP).</td>
<td>• Capability to produce new parts in space reduces reliance on access from Earth, which may be disrupted in a conflict.</td>
<td>• Support to government industrial strategy and priorities for supporting high value manufacturing (exports, jobs, IP).</td>
</tr>
<tr>
<td>Fiscal contribution of a more productive and competitive manufacturing sector, whether in space or on Earth.</td>
<td>• Increased longevity and self-sustainment for military systems and missions in space, providing cost and tactical benefits.</td>
<td>• Fiscal contribution of a more productive and competitive manufacturing sector, whether in space or on Earth.</td>
</tr>
<tr>
<td>Ability to produce parts for civilian missions in space on-demand, making possible new, longer mission types.</td>
<td>• Reduced logistics footprint and associated force protection-requirements for military forces on Earth, exploiting the spillover applications of IIoT and advances in ISRU.</td>
<td>• Ability to produce parts for civilian missions in space on-demand, making possible new, longer mission types.</td>
</tr>
</tbody>
</table>
## Civil (commercial)

- Creation of new space and terrestrial markets for the products of specialised space-based manufacturing.
- Reduced cost and increased performance and longevity for commercial space missions, e.g. assembly, repair or upgrade of communication satellites in LEO or Geostationary Orbit (GEO).
- Improved productivity for terrestrial manufacturing facilities and workforces due to use of IIoT, boosting competitiveness.
- Improved design through use of IIoT to provide real-time data on products’ performance over time, enabling refinement.
- Improved integration and real-time remote monitoring of manufacturing supply chains enabled by satellite connectivity.
- Creation of new support markets e.g. servitisation with shift towards providing through-life support services backed by IIoT, and predictive rather than reactive repairs.

## Civil (other)

- Ability to fabricate and assemble equipment for scientific and exploration missions in space, reducing costs and increasing mission flexibility and duration.
- Potential for trade unions and other manufacturing advocacy groups to use satellite data in their operations, e.g. to monitor employers’ compliance with regulations.

## Consumers

- Access to increase variety of finished goods, whether produced in space or by space-enabled factories on Earth.
- Reduced costs for consumer products arising from advances in productivity and competitiveness of manufacturing sector.

### Estimate of timeframes

The ISS has already hosted a range of experiments and proofs-of-concept relating to on-orbit manufacturing in microgravity conditions. This includes successful 3D printing of plastics in space for the first time in 2014, using a 3D printer produced by Made In Space, who subsequently partnered with NASA on the installation of an upgraded Additive Manufacturing Facility (AMF) on the ISS in 2016. In 2018, a Refabricator system developed by Tethers Unlimited was also installed on the ISS to demonstrate a repeatable closed-loop process of recycling plastic materials, and using these as feedstock for new on-orbit manufacturing. Looking to the future, specialised manufacturing processes tailored to microgravity are expected to continue to mature through the 2020s and into the 2030s. This is backed by various NASA and other government-backed research programmes, as well as ongoing commercial R&D efforts.
Initial markets for space-made products are expected to focus on high-value items. For example, US optical fibre manufacturers Thorlabs has already partnered with Made In Space to refine and test on ISS the processes for producing high-quality optical fibre on orbit; if successful, this will be the first commercial product manufactured in space. The Factories in Space database provides estimates of Technology Readiness Levels (TRLs) for possible future initial space-made products. Examples include:

- Bulk metallic glass (TRL 6);
- Diamond (TRL 6);
- Medicine and drugs (TRL 5);
- Organic tissue including organs (TRL 4);
- Perfect spheres for microscopes and other applications (TRL 9);
- Silicon carbide (TRL 7);
- Ultra-thin coatings (TRL 6); and
- ZBLAN and exotic fibres (TRL 7 to 8).

Beyond high-value items used to feed other industrial processes, such as the above, there is also scope for near-term manufacturing of novelty items (e.g. beer, chocolate, coffee, fragrances) for terrestrial luxury markets. The development of larger scale manufacturing efforts in the 2040s and beyond will be dependent on refining fabrication processes, having access to sufficient and affordable supplies of raw materials (e.g. from space-based resource extraction), and the upfront costs of launching and constructing the necessary facilities in space.

The large-scale roll-out of space technologies that enable IIoT and the transition towards Industry 4.0 in terrestrial manufacturing represents a more near- and medium-term proposition. Realising the benefits of Industry 4.0 by 2030 forms an important component of many government and commercial strategies for the future of manufacturing, with digital factory revenues expected to increase from $59bn in 2019 to $375bn in 2030 according to industry projections.

For further information on likely timelines for adoption of next-generation SATCOM and PNT services as an enabler for the IIoT, see Annex N on ‘Telecommunications’.

### Drivers and enablers

Future space-based manufacturing may be enabled by continuing innovation in a variety of technical fields, contributing to increased efficiency and cost-effectiveness of several of the use cases described above. These include continuing advances in:

- IIoT technologies and techniques, including additive manufacturing and closed-loop systems.
- Embedded sensors for monitoring industrial processes in the tightly controlled environments of any orbital production facility.
- Materials, biotechnology and nanotechnology, providing new materials for manufacturing processes as well as enabling miniaturised designs and new fabrication techniques, such as smart materials for ‘self-organising and self-assembly, using biometric techniques similar to what occurs with DNA or enzymes to control deposition’.

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383 O’Connell (2019).
384 Factories in Space (n.d.).
385 Zirconium Barium Lanthanum Aluminum Sodium Fluoride (ZBLAN).
386 OECD (2004).
Robotics and AI/ML for automation of industrial processes to optimise performance over long periods, including in challenging and changing environments, such as in space.

In addition to technological progress, the development of space-based manufacturing out to 2050 may be facilitated by increasing demand for ISRU and fabrication of parts, equipment and structures as the wider space economy and population continues to grow. The costs of launch mean that, should advances in space-based resource extraction (see Annex G on ‘Extractive industries’) enable easy, timely and affordable access to the necessary materials, there should be strong demand for space-based production of supplies needed to sustain long-duration missions and facilities.

At the same time, the benefits of microgravity to production of certain niche products (e.g. 3D printing of liquids and soft materials – such as human tissue – that would collapse under their own weight on Earth) provide a strong business case for further investment to meet demand from terrestrial markets. Similarly, the projected value of future IIoT in terrestrial manufacturing incentivises continuing development of next-generation SATCOM and PNT services.

### Potential barriers and challenges to implementation

There are both persistent technical and non-technical barriers to realisation of more ambitious plans for space-based manufacturing out to 2050.

The type of object that can be created in space may be limited due to diverse practical reasons, such as the requirements of component materials for a specific structure, the dimensions of the item to be created, the time needed to perform the architecture, the object’s features to be manufactured, and the required power to fuel the operation process. As an example, the 3D printer in the ISS currently only uses polymer as feedstock, but many objects require other materials, such as metals and composites.389 Just as certain industrial processes benefit from microgravity conditions, others do require gravity. Challenges are also found in reaching the demanded accuracy to create complex structures, or the lack of gravitational acceleration, exposure to radiation, existence of atomic oxygen, and possible impacts on space-based facilities from other objects in the space environments (debris, or micrometeorites).

The costs of launching and constructing large-scale facilities, and the uncertain commercial viability of these installations and product lines compared to established factories on Earth, also represent a major barrier to space industrialisation at scale. This certainly applies to the long-term plans of individuals such as BlueOrigin founder Jeff Bezos for a ‘paradigm shift’ towards moving most manufacturing into space to enable widespread de-industrialisation of the Earth as a ‘national park’ (see Annex B on ‘Climate and environmental protection’).

In the roll-out of space-enabled IIoT technologies, there are also enduring concerns about cost, data and cybersecurity, the impact of automation on jobs, and the impact on small and medium enterprises in the supply chain who may not have sufficient funds or skills to adapt to the IIoT in the way that larger manufacturers and prime contractors can.

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389 Boyd et al. (2017).
## Summary of potential impacts and implications for the space economy

<table>
<thead>
<tr>
<th>Category</th>
<th>Potential Impacts and Implications</th>
</tr>
</thead>
</table>
| **Prosperity**                         | • Reduced costs of establishing and maintaining other missions and installations in space, given ability to manufacture in-situ.  
• Economic benefits of space-based manufacturing and innovation in microgravity production techniques.  
• Economic benefits of space-enabled advances in productivity and competitiveness of manufacturers on Earth.  
• Optimisation of designs, fabrication equipment and processes through use of space-enabled IIoT technologies.  
• Automation of certain manufacturing jobs (e.g. in favour of robotic assembly) leading to creation of new demands for certain skills and professions (e.g. in programming, AI/ML, cyber). |
| **Environment & net-zero economy**     | • Advances in recycling unneeded components in space for manufacture of new space objects or structures.  
• Innovation in closed-loop processes and waste reduction, with spillover applications to manufacturing on Earth.  
• Long-term potential to shift heavily polluting industrial processes into space, de-industrialising the Earth and helping to reduce carbon emissions and air and water pollution. |
| **National security & defence**        | • Improved ability to sustain military missions and installations in space at reduced cost and in times when access to space is disrupted, e.g. by hostile action during a conflict.  
• Innovation in advanced manufacturing techniques for space with potential spillover applications in a defence context.  
• Benefits of IIoT to the national defence technological and industrial base (DTIB) and to supply-chain development.  
• Increased manufacturing activities in space increases the need for effective SSA/SST and other measures to secure space. |
| **Science & discovery**                | • Advance in techniques to construct and assemble space objects and installations in-situ for scientific purposes.  
• Support for long-duration exploration missions and establishment of lunar, Martian or other colonies.  
• Innovation in various technical disciplines (e.g. materials, nanotechnology) driven by advances in space-based manufacturing and IIoT in terrestrial industrial processes. |
| **International collaboration**        | • Continuing role of ISS in supporting experimentations in space-based manufacturing equipment and processes.  
• Opportunities to reduce cost of joint international space programmes through greater use of ISRU and manufacturing.  
• Opportunities to develop new collaborations between upstream space manufacturers around adoption of IIoT. |
Science, research and education

Definition
This cluster comprises all those activities in or enabled by space that are focused on advancing human knowledge and understanding of the physical, natural and social world through systematic application of the scientific method and the dissemination of knowledge through educational means.

Summary
For decades, the space sector has represented a key driver for scientific exploration, research and innovation by both civil and military actors. With space exploration remaining a key ambition for both space-faring nations and commercial actors, future uses of space to 2050 include a wide range of new mission types for space exploration as well as exploitation of wider space-enabled applications for scientific, research and educational purposes on Earth.

While some types of scientific mission – such as microgravity research and experimentation aboard the ISS – have already been carried out for decades, there is growing interest in revisiting the Moon (and establishing permanent research facilities on its surface) as well as exploring Mars and other distant parts of Earth’s solar system. Given competition between nations and strong interest from commercial space actors, it is possible that crewed interplanetary missions may be realised by the 2030s.

International research collaboration is also likely to continue on the most resource-intensive technical projects, such as the development of future large-scale experiments and research infrastructure (e.g. the 2021 launch of the James Webb Space Telescope and any eventual successor). Improvements in space robotics, sensors, propulsion and energy systems will also open new possibilities for complex, long-duration uncrewed missions, and potentially even the development of interstellar missions (e.g. using lasers and solar sails to propel nano-ships to Alpha Centauri) out towards 2050.

Outside of exploring space, space-based technologies – including low-cost CubeSats and SmallSats, as well as satellite services (EO, SATCOM, PNT etc.) – will continue to play an important role in contributing a variety of benefits to terrestrial science, research and education markets. In future, this could include generation of vast new data-sets for real-time analysis (e.g. using AI/ML), improved connectivity between research teams around the world (or in orbit), and global access to e-learning tools.

Despite the extensive contributions of space-based applications for research and education, the scope and rate of progress for new innovation will be dependent on sufficient funding being available, enduring technical barriers being overcome, and scientists being able to build sustained public and political support for investing finite resources in space exploration rather than to address other pressing matters on the policy agenda (e.g. climate change, health, jobs).
### Relevant use cases

- **Microgravity experiments**: The condition of microgravity offers a unique context for scientific experimentation, particularly in biological and human sciences. There are currently more than 300 scientific experiments being conducted in microgravity aboard the ISS.\(^{390}\)

- **Other space-based experiments**: Future space-based scientific experiments may include variable gravity research, including research examining life support development (e.g. effects of lunar or planetary gravity levels on plants and animals).\(^{391}\)

- **Suborbital missions**: Suborbital exploration includes the use of suborbital airborne, balloon and rocket elements for scientific purposes – such as EO, climate research, astrophysics and solar-terrestrial observations – and support for satellite mission instruments and data through calibration and validation.\(^{392}\)

- **Interplanetary missions (crewed)**: There are various plans to land on Mars in the next two decades and explore other bodies (e.g. Saturn’s or Jupiter’s moons) in the longer term.

- **Interplanetary missions (uncrewed)**: Advances in robotics and autonomy open new possibilities for science and exploration missions to the Moon, Mars, comets, asteroids and other planets and moons in the solar system.\(^{393}\) In addition to improvements in traditional probes, landers and rovers, new types of vehicle might enable novel mission types, e.g. autonomous submarines to explore Titan’s hydrocarbon seas,\(^{394}\) or swarming robots that build research sites through in-situ resource utilisation (see Annex G on ‘Extractive Industries’).

- **Interstellar missions (uncrewed)**: Interstellar missions are characterised by their scope beyond the heliopause and the Solar System. Current concepts include ‘interstellar precursor’ missions using existing technologies, or more ambitious plans for new approaches such as laser-powered space sails.\(^{395}\)

- **Human-Machine Teaming (HMT) for science and exploration**: Options for such hybrid missions include different modes for HMT and autonomy, ranging from cooperation on tasks inside and outside of a pressurised habitat, crew and robots operating independently and coordinating tasks as needed, and robots operating independently of the crew.\(^{396}\)

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392 NRC (2010).
393 Wall (2019).
394 Tangermann (2018c).
395 David (2019).
396 Parrish et al. (2017).
<table>
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<tr>
<th>Hybrid markets</th>
</tr>
</thead>
</table>
| • **Robonautics for science and exploration**: Advances in AI/ML and autonomy may enable new types of complex, long-duration missions that are not feasible when relying on remote control. Advances in robonautics and additive manufacturing may enable bootstrapping of entire extra-terrestrial ‘self-sustaining, self-expanding’ research sites through a spiral of ISRU.  

• **Low-cost miniaturised systems for science and exploration**: Departing from the current platform-centric model, future missions could exploit swarms of low-cost smallsats and CubeSat capabilities for near-term deep space explorations (e.g. beyond Jupiter). Soft robotics may similarly represent a more low-cost, resilient option of robotics for exploration. Advances in nanotechnology may facilitate novel concepts, such as Micro-Probes Propelled and Powered by Planetary Atmospheric Electricity (MP4AE), creating large swarms of microprobes and string loops that exploit atmospheric drag and electrical charge as a power source.  

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| Search for Extra Terrestrial Intelligence (SETI): SETI encompasses search for signs of sentient life beyond Earth. Future advances in SETI capabilities may include various techniques for detecting activity from deep space, such as advanced high-sensitivity cameras for detecting laser light.  

• **Messaging Extra Terrestrial Intelligence (METI)**: Also referred to as Active SETI, METI includes design and transmission of interstellar messages to contact other civilisations – a largely unregulated, potentially high-risk and controversial activity.  

• **School, university and hobbyist use of space**: Future space applications may include direct support to primary, secondary and higher education, including through teaching and hobbyist projects such as rocket and smallsat launches.  

• **Citizen science and exploration**: In future, space missions may increasingly be conducted by amateur ‘citizen’ scientists. Current concepts envision suborbital flights for citizen scientists as well as Martian science observations enabled through 3D augmented reality (AR) gaming infrastructures. Similarly, EO, SATCOM and PNT may all be utilised to encourage participatory and open science initiatives on Earth.  

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397 Metzger et al. (2013).  
398 Szondy (2019).  
399 Fingas (2019).  
400 Szondy (2019).  
401 METI International (n.d.).  
402 SETI Institute (n.d.).  
403 METI International (n.d.).  
404 Meyer (2013).  
405 Mercer & Landis (2017); Citizens in Space (n.d.).
Terrestrial markets

- **Novel data-sets for research and analysis**: Advances in EO and PNT provide the opportunity to generate vast volumes of real-time data on changes in the physical, natural and social world for fusion, analysis and use in modelling.

- **Connectivity for e-learning**: Satellite-enabled tele- and video-conferencing and broadband coverage may be used to provide connectivity for e-learning and tele-education, facilitating distance learning, including for remote areas, as well as development of innovative educational techniques.406

- **Connectivity for research teams and facilities**: Space-based services may further support terrestrial research through providing connectivity for research teams and facilities, encouraging global collaboration and remote working.

### Main actors

The falling costs of access to space and proliferation of low-cost satellites present opportunities for an increasing range of actors to participate in space-related research and exploration, as well as to integrate space services into scientific or educational programmes on Earth.

This moves beyond the traditional government (e.g. NASA, ESA), military (e.g. DARPA, Dstl) and academic institutions (e.g. universities, independent research institutes and funding councils) to include schools and even individual citizens who can utilise increasingly low-cost satellite and launch technologies for research, education or hobbyist purposes.

Government agencies have increasingly recognised the benefits of deepening collaborations between professional scientists and interested members of the public, exploiting their skills, insights and relevant assets (e.g. the processing power of networked PCs), and fostering stronger public awareness of and support for space exploration missions (i.e. outreach). In the United States, for example, NASA’s Science Mission Directorate has made additional funding available in the 2020 call of its Research Opportunities in Earth and Space Science (ROSES) programme for proposals incorporating citizen science. As of July 2020, the Agency has over 20 live projects involving citizen scientists,407 and maintains NASA Solve as a central repository bringing together scientists, students and the public.408

Commercial actors (e.g. Boeing, BlueOrigin, SpaceX) and NewSpace companies also play an increasingly important role in supporting or conducting space exploration and space-based scientific research through R&D, launch of specialist payloads and suborbital or orbital exploration missions.409

### Value proposition to end users

**Government (civil)**

- Improving understanding of the physical, natural and social world, leading to innovation and practical applications.
- Contributing to national pride and prestige, demonstrating technical achievements to the global community.
- Supporting provision of scientific evidence to policymakers and development of technical solutions to problems.

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406 UNOOSA (n.d.b).
407 NASA (2020c).
408 NASA (2020d).
<table>
<thead>
<tr>
<th>Category</th>
<th>Benefits</th>
</tr>
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</table>
| Government (military) | • Fostering national capabilities in science and research, in government and the wider industrial and academic base.  
                          • Supporting skills development and sustainment, particularly for Science, Technology, Engineering and Maths (STEM).  
                          • Improving access to and understanding of the space domain.  
                          • Producing insights on space-based applications of relevance to military capabilities (i.e. delivering operational advantage).  
                          • Supporting a competitive and sustainable technological and industrial base (i.e. enhancing national freedom of action).  
                          • Generating beneficial spillovers between civil, dual-use and military technologies first developed for space exploration. |
| Civil (commercial)  | • Innovation and development of new Intellectual Property (IP) and new markets, products and services.  
                          • New market opportunities provided by use of commercial spaceflight to launch R&D payloads.  
                          • New market opportunities for crewed suborbital flights aimed at providing training for astronauts on exploration missions.  
                          • Additional market opportunities arising from beneficial spillovers between space science and technology and other sectors (e.g. health, manufacturing and logistics). |
| Civil (other)       | • Enabling affordable access to space, previously the sole domain of large government and commercial organisations.  
                          • Democratising the conduct of space-related science and exploration, ensuring a wider diversity of perspectives.  
                          • Providing new research funding and collaboration opportunities for universities and research institutes.  
                          • Providing new tools and capabilities for delivering teaching and research, including remotely. |
| Consumers           | • Enhancing access to education, including e-learning for remote communities, benefitting all aspects of life and career.  
                          • Fostering increased awareness of deep-space exploration and the benefits produced by space-based scientific research.  
                          • Potential engagement in citizen space-exploration missions, including through new mission concepts, such as augmented-reality-enabled exploration. |

**Estimate of timeframes**

Space exploration may significantly evolve out to 2050 due to advances in spacecraft designs as well as robotics, AI/ML, materials, propulsion, energy systems and other enabling technologies. Different nations and multinational organisation are working to differing timelines for future exploration, though there is a common iterative approach to many governments’ future roadmaps.
In the United States, for example, NASA aims to return crewed spacecraft to the Moon as a precursor to missions further afield. This involves landing astronauts in the lunar South Pole by 2024 and developing a constellation of exploration capabilities around the Space Launch System (SLS), the Orion spacecraft and Gateway lunar command module. The SLS would then be used to launch robotic scientific missions to Mars, Saturn, Jupiter and beyond, as well as potential crewed missions to Mars by the 2030s. China is aiming to land astronauts and establish a base on the Moon by 2035, before also launching crewed missions further into the Solar System. The ESA, Russian, Japanese and Indian space agencies all have their own plans for future uncrewed and crewed missions, while even small and recent space-faring nations such as the United Arab Emirates have ambitious plans for national exploration missions – with the UAE launching its first interplanetary probe, the Hope Mars Mission, in July 2020. Several commercial actors are proposing more aggressive timelines, arguing that national governments are constrained by excessive safety concerns, bureaucracy and a lack of innovation. SpaceX has stated its plans to launch its first uncrewed cargo missions to Mars in 2022, providing supplies that would be used to support a crewed mission in 2024. There are also plans to go far beyond Mars; the Mark Zuckerberg- and Stephen Hawking-backed group Breakthrough Initiatives, for example, aims to send 1,000 nano-ships powered by laser light sails to Alpha Centauri. This would commence from around 2036, with so-called ‘StarChips’ completing the 4.37 light-year journey in the course of around 20 years, by reaching speeds of 15–20 per cent of the speed of light. Besides exploration missions, a series of large-scale and ambitious scientific initiatives is planned for realisation out to 2050. This includes future experiments on the ISS, the launch of the James Webb Space Telescope in 2021 and the ESA’s Laser Interferometer Space Antenna in 2034.

Drivers and enablers

In recent years, space exploration has extensively benefited from the commercialisation of spaceflight and the emergence of low-cost commercial spaceflight markets. Further to directly enabling space exploration, for instance, through carrying R&D payloads to space missions, commercial spaceflight may enable the refocusing of resources in the civil space sector to scientific research and exploration. The development and proliferation of low-cost smallsats and cubesats has also enabled wider applications in science and research, including by schools, universities and hobbyists. Cubesats enable significantly lower cost of scientific and educational applications in space. Advances in robotics, human-robotic interfaces and human-machine teaming technologies, as well as innovative manufacturing techniques (e.g. additive manufacturing) also represent key technological enablers for future space exploration through enabling the capturing of increasing amounts of data and generating insights with more potent research capabilities.

Potential barriers and challenges to implementation

Space exploration includes a wide range of methods of space exploration that each face various technical and non-technical barriers – not least financial cost – to further adoption and development. For instance, certain forms of space exploration, including suborbital programmes, have historically suffered from lack of funding and challenges related to skills and workforce sustainment. Future space exploration may face barriers related to decreasing public interest in space exploration and limited public support for high-cost or dangerous endeavours, including crewed missions or interstellar exploration, given competing demands on finite resources.

411 Bartels (2020).
412 Brown (2020).
413 McNamara (2019).
414 Meyer (2013).
415 NRC (2010).
The realisation and improvement of space exploration missions – such as interstellar exploration – faces barriers related to the speed of current spacecraft and propulsion technologies. Current concepts for larger interstellar probes, for example, envision a mission launched before 2030 to reach 1,000 Astronomical Units (AU) in 50 years, while even the tiny microchips envisaged as the payload for Breakthrough Initiatives’ ‘StarChips’ concept would take two or more decades to reach Alpha Centauri and require an array of powerful lasers on Earth to propel them on their journey.416

Although low-cost smallsats and cubesats in Low Earth Orbit (LEO) have enabled an increasing number of science and education applications in space, they also exacerbate the risk of space debris.

The scientific basis of space-based research techniques – such as SETI and METI – have been disputed, and their governance arrangements are controversial. Disputes among the scientific community concerning the value and potential risks of SETI versus METI research, as well as funding challenges, have presented barriers for advances, in this area and raised concerns about the possible dangers of drawing the galaxy’s attention to humanity.417

Summary of potential impacts and implications for the space economy

<table>
<thead>
<tr>
<th>Prosperity</th>
<th>Environment &amp; net-zero economy</th>
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</thead>
<tbody>
<tr>
<td>• Market opportunities (and associated jobs, exports etc.) for commercial space operators supporting scientific missions.</td>
<td>• Advances in the development of space-based applications for environmental protection and sustainable energy.</td>
</tr>
<tr>
<td>• Market opportunities (and associated jobs, exports etc.) for schools, universities and e-learning specialists.</td>
<td>• Spillover benefits from space-related technology developments to other parts of the green economy.</td>
</tr>
<tr>
<td>• Innovation and the development of new value chains as a result of advances in space science and engineering.</td>
<td>• Advances in citizen science and other collaborative platforms for researching common issues, such as climate change.</td>
</tr>
<tr>
<td>• Spillover benefits to other parts of the global and national economy arising from advances in space-related fields.</td>
<td>• Advances in e-learning, benefitting remote communities in areas hit by natural disaster and cutting travel emissions.</td>
</tr>
<tr>
<td>• Increased workforce productivity due to improved education and development of the STEM skills pipeline.</td>
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</tr>
</tbody>
</table>

416 David (2019).

417 Scientists disagree as to the explanation for the Fermi paradox – the fact that the universe is made up of vast numbers of stars and planets, implying statistically that sentient life should be abundant, and yet there has been no proof of extra-terrestrial life to date – but some fear that other, more advanced, civilisations may know to stay silent to avoid exposing themselves to predation or other dangers (often known as the ‘dark forest’ explanation). Source: Deshmukh (2019).
### National security & defence
- Improved insights on physical, natural and social phenomena, benefiting military and police strategy, policy and plans.
- Advances in technology for dual-use applications, benefiting defence and security-related capabilities and operations.
- Contribution to sustainment and development of national aerospace sector and defence industrial and research base.
- Further impetus to driving down costs of access to space, benefitting military space operations.
- Increased need for robust SSA/SST to mitigate risks arising from the democratised use of space for scientific purposes.

### Science & discovery
- New space-based infrastructure for supporting research into space and terrestrial phenomena.
- Provision of new data for research and analysis, as well as special conditions (e.g. microgravity) for experimentation.
- Support to integration of global research teams and space-enabled services for research (EO, SATCOM, PNT etc.).
- Increased public awareness and support for deep-space exploration and space-based scientific research (outreach).
- Increased public participation in space-related scientific research initiatives (citizen science).
- Provision of improved access and new tools for e-learning and traditional in-person education.
- Recruitment of future generation of scientists and increased support for STEM skills development and sustainment.

### International collaboration
- Potential for international collaboration on science and research, including deep-space exploration missions.
- Potential for satellite-enabled cross-border collaboration between different international research teams.
- Potential for international collaboration on SETI and METI, including development of first-contact protocols.
- Improved understanding of humanity’s place in the Universe as driver of cultural and normative change in global society.
Annex N. Telecommunications

**Telecommunications**

**Definition**

This cluster comprises all those activities in or enabled by space that are focused on enabling the transmission of information in analogue or digital form between multiple locations through the means of electrical signals or electromagnetic waves.

**Summary**

Telecommunications services, including broadband, are increasingly integral for government, military and commercial users as well as the everyday lives of individual consumers. Connectivity underpins many of the basic functions of modern digital society and the global economy and financial markets. Existing estimates indicate that UK Internet traffic, for example, is predicted to grow five-fold between 2018–2023 alone, driven by the proliferation of networked technologies – such as the Internet of Things (IoT) – and the more widespread adoption of cloud computing in civil and commercial sectors, along with consumer entertainment applications such as streaming and online gaming services.\(^\text{418}\) Such trends increase requirements for faster data download and upload speeds, lower latency and improved coverage, reliability and security of connectivity to provide ‘accessibility on the move’.\(^\text{419}\)

SATCOM and other services, most notably PNT, already play a crucial role in supporting global telecommunications alongside other means, such as undersea optical cables, mobile telephony infrastructure, or networks of copper and fibre cabling on land. In future, advances in satellite technologies and adjacent areas, such as improved antennae and software design, offer new prospects for next-generation SATCOM services. This includes use of mega-constellations of smallsats and cubesats in LEO to establish space-based infrastructure for global Internet coverage and support future 5G and 6G applications, even in the most remote areas.

Such innovations aim to enable improved multimedia delivery, broadband, machine type communications, critical communications (e.g. for emergency services) and vehicular communications (e.g. bringing broadband, calls and data relating to Intelligent Transport Systems to cars, lorries, trains, aircraft and ships in transit).\(^\text{420}\) Given their position in orbit, satellites offer a range of unique advantages to replace or complement alternative communications infrastructure on Earth as part of hybrid networks.

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\(^{418}\) Catapult Satellite Applications (2017).

\(^{419}\) Catapult Satellite Applications (2017).

\(^{420}\) Eneberg (n.d.).
Looking to the future, advances in in-space communications are also required to ensure robust and resilient communications for a growing number of spacecraft and orbital, lunar or Martian facilities. Although there are significant opportunities for space-based applications to enable future telecommunications services and applications, there are several barriers to overcome. These include the growing need for effective electromagnetic (EM) spectrum management as the number of space objects increases; growing threats of cyber, electronic and physical attacks on satellite systems and networks; financial barriers for innovative start-ups looking to enter the market; and cost barriers in relation to access to space.421

### Relevant use cases

<table>
<thead>
<tr>
<th>Space markets</th>
<th>Hybrid markets</th>
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<tbody>
<tr>
<td><strong>In-space laser communications</strong>: Laser communications may improve in-space communications and replace techniques based on shorter range RF communications.422 Relays may help create a network across the Solar System.</td>
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<tr>
<td><strong>LEO satellite constellations</strong>: SmallSat constellations in LEO may bring significant improvements to telecommunications services by enabling low-latency connectivity. The latest examples include the Iridium constellation of 66 satellites providing pole-to-pole coverage for voice communications.423</td>
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<tr>
<td><strong>LEO to GEO terrestrial communications</strong>: LEO-to-GEO optical intersatellite communications using laser communication terminals or other technologies may help boost resilience and reliability of broadband connectivity for end users by switching between LEO and GEO communications.424</td>
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<tr>
<td><strong>Fixed satellite communication services</strong>: Fixed satellite-service broadband systems are placed within fixed, specific areas to both broadcast and receive communication signals. Future market opportunities include satellite broadband for rural areas and enterprise sector machine-to-machine (M2M) and IoT-related services.425</td>
<td></td>
</tr>
<tr>
<td><strong>Mobile satellite communication services</strong>: In contrast to fixed satellite services, mobile satellite services may be moved from one location to another (e.g. on moving vehicles). Though conventionally these have been utilised in the maritime and other transport sectors and mobile telecommunications, existing research projects a potential future convergence in markets provided by fixed and mobile satellite services.426</td>
<td></td>
</tr>
</tbody>
</table>

421 Catapult Satellite Applications (2017o).
422 Chen (2018).
426 Kurtin (2012).
• **Space-based global broadband communication services**: Current perspectives on future applications of satellite-enabled connectivity services envision the potential for global broadband (5G/6G) coverage. Current forecasts estimate global broadband to be a fast-growing £40bn market. 427

• **Satellite backhaul to support both cloud and edge computing**: Satellite services may facilitate cloud computing (‘shared access to remote computing sources’) and edge computing, which is increasingly relevant in sectors utilising IoT.

• **Space laser communication technology for ultra-high-speed data transmission**: Laser communications may enable ultra-high-speed inter-satellite and satellite-to-ground data transfer. This may benefit deep-space, orbital or terrestrial communications.

• **Flexible satellite infrastructure**: Telecommunications has seen an increasing demand for flexible or ‘reprogrammable’ satellite technologies from operators. Flexible satellites may provide flexibility for providers by shifting between different services, e.g. television broadcasting and broadband connectivity, based on fluctuating demand. 428

• **In-space communications relay**: Future data transfer with ground may be enabled through Tracking and Data Relay Satellites (TDRS) to maintain constant global coverage of satellites without the need for additional ground stations. 429

• **Quantum-encrypted communications**: Advances in quantum technologies offer the prospect of ‘unconditionally secure’ encrypted long-distance satellite-to-ground and inter-satellite optical communications using quantum key distribution. 430

• **Space-based data centres**: Novel future space-based telecommunications markets may include the locating of data centres (i.e. servers and relevant power supplies) directly in space. This may bring long-term cost-saving benefits as well as increased security, enhanced performance through microgravity, and decreased signal transmission times.

• **Electromagnetic spectrum management**: Effective EM spectrum management encompasses the ‘oversight of RF spectrum use’ with the aim to ‘prevent users from harmful interference while allowing optimum use of the spectrum’. Spectrum management encompasses planning (spectrum allocation), licensing (authorisation), regulatory (engineering) and enforcement (compliance) functions and services. 431

428 Henry (2019).
430 Jet Propulsion Laboratory (n.d.a).
Terrestrial markets

• Direct-To-Home (DTH) broadcasting: Direct-To-Home (DTH) broadcasting accounts for 48 per cent of the UK space industry, according to a 2018 estimate. Despite increasing demand for cable and fibre-optic alternatives to DTH, current perspectives indicate that future DTH markets may expand to remote areas where coverage is currently not realised.

• Specialist services for rural and remote locations: Future space-based communications services may ensure connectivity for rural or remote areas, including the Arctic and Antarctic.

• High-altitude pseudo satellite (HAPS) services: Advances in autonomy and suborbital flight have led to increased convergence between LEO satellites and airborne systems, for example balloons and the solar-powered Zephyr UAS, which can fly for days at 70,000ft to act as a mobile communications relay.

Main actors

The global telecommunications industry involves a mix of government, civil, military and commercial actors across its complex value chains, as well as international bodies such as the International Telecommunication Union (ITU), a specialist agency of the United Nations. Many of these different organisations are actively involved in advancing efforts towards next-generation SATCOM services and other space-enabled applications.

Government agencies such as NASA are engaged in R&D and experimentation to develop new systems for in-space communications in support of future exploration and communication missions. This includes partnerships with commercial and research organisations to explore areas such as interplanetary optical communications, Deep Space Optical Communications (DSOC) and high-rate and power-efficient radio-frequency (RF) technologies. Beyond civilian programmes, US military agencies such as DARPA have also advanced research projects on telecommunications services, such as LEO-to-GEO communications.

China has similarly played a leading role in advancing quantum communications satellites, launching the world’s first such satellite, Micius, in 2016. In Europe, the ESA and commercial actors including Airbus are similarly currently pursuing laser communication projects guided by the view that ‘lasers – not radio – are the future of space data’. Within the UK, ‘Ubiquitous Connectivity’ is one of the stated focus areas of the Catapult Satellite Applications, while ‘Satellites in 5G Connectivity’ is also a priority within another Catapult Satellite Applications focus area for Emerging Technologies.

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432 Sabri (2020).
433 Tobin (2018).
434 Catapult Satellite Applications (2017u).
436 Jet Propulsion Laboratory (n.d.b).
437 Strout (2019).
439 Chen (2018).
440 Catapult Satellite Applications (2020d).
441 Catapult Satellite Applications (2020c).
There is also a wide variety of major industry players actively innovating in this area. This includes satellite manufacturers and operators, specialist telecommunications service providers, mobile network operators and major multinationals (e.g. AT&T, Verizon, Vodafone). The UK is home to a number of significant players in the satellite communications market, including Inmarsat, AeroMobile, Avanti Communications, iSat LTD and NSSLGlobal Ltd.

Other international players include SES, Viasat, Intelsat, Eutelsat and Telesat. In addition to larger economies such as the United States, France, Canada and Japan, several leading companies (e.g. SES, Intelsat) have headquarters or major operations in Luxembourg, reflecting efforts by the Grand Duchy to promote a favourable business environment for space firms.

Major firms involved in development of space-based global 5G coverage include Airbus, SpaceX, OneWeb, Amazon, Facebook, Avanti Communications, Eutelsat, Gomspace, Gilat Satellite Networks, OHB SE, Quortus, Boeing and Thales. Leading aerospace manufacturers Airbus, Boeing and Thales currently also provide reprogrammable or ‘flexible’ satellite services. There has also been speculation about the potential for collaboration between firms such as BlueOrigin and Amazon Web Services, both owned by Jeff Bezos, on future development of space-based data centres.

### Value proposition to end users

#### Government (civil)

- Providing connectivity for secure government SATCOM.
- Providing connectivity for various critical functions, such as the emergency services or air traffic management.
- Ensuring resilience of telecommunications to prevent disruption and facilitate other sectors and markets.
- Ensuring connectivity for remote communities and government installations in space or on Earth (e.g. in the Arctic).
- Providing market opportunities for telecommunications industry through funding, policy and regulatory incentives.

#### Government (military)

- Greater resilience and security of military communications, e.g. through LEO-to-GEO capabilities or quantum encryption.
- Increased bandwidth and coverage to support military command, control, communications, computers, intelligence, surveillance and reconnaissance (C4ISR) around the globe.
- Support for precision strike capabilities, enabling modern network-centric warfare even in austere environments.
- Access to commercial SATCOM services on demand, with technological advances enabling new commercial models for outsourcing, e.g. ‘SATCOM as a Service’.

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442 BIS Research (2020).
443 Henry (2019a).
### Civil (commercial)
- Growing market opportunities in telecommunications.
- Ensuring connectivity for roll-out of IoT devices, including for sectors reliant on cloud and edge computing.
- Enabling wide variety of downstream applications and related markets, e.g. high-resolution video streaming services.
- Access to new markets and audiences in rural and remote areas, including countries without ground-based infrastructure.

### Civil (other)
- Connectivity for rural and remote areas, including the polar regions and areas where telecommunications infrastructure is immature or damaged by conflict or natural disaster.
- Facilitating scientific research through increased bandwidth and reduced latency for transferring vast data-sets.

### Consumers
- Ubiquitous coverage (including broadband to moving platforms, such as vehicles), increased reliability and improved network performance.
- Increased choice of high-quality and more affordable mobile and broadband services.
- Facilitating wide range of applications and services, e.g. mobile banking and retail, consumer IoT and entertainment.

### Estimate of timeframes

Satellite communications have been a major contributor to the evolution of modern digital society over past decades, and both their capabilities and affordability continue to evolve. Current projections estimate significant advances in space-based telecommunications services out to 2030 and beyond. This includes continuing growth in more mature markets (e.g. fixed and mobile satellite communications), as well as new and emerging areas. For example, current predictions indicate that innovation in laser communications technologies may allow them to reach rates of 30–40Gbps out to 2030, and up to 100Gbps by 2050.446

The global 5G satellite communications market is similarly projected to grow at a compound annual growth rate (CAGR) of close to 29 per cent between 2021–2030.447 Many large companies have ambitious plans to build and operate mega-constellations of smallsats in LEO to provide global Internet connectivity; SpaceX, for example, hopes to launch an initial 12,000 Starlink satellites in the early 2020s and has applied through the US Federal Communications Commission (FCC) to the ITU for approval for another 30,000 thereafter.448 Before entering into financial difficulties, OneWeb had hoped to complete its initial 650-satellite constellation and begin providing global satellite Internet broadband services in 2021, and had applied to the FCC for approval for another 48,000 satellites.449

Out to 2050, other inter-satellite and satellite-to-ground communications technologies may also further mature, enabling ultra-high-speed data transmission – e.g. through laser communications – and with more widespread use of quantum-encrypted communications for enhanced security.450

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446 Guo & Wu (2010).
447 BIS Research (2020).
448 Henry (2019b).
449 Hill (2020).
450 Guo & Wu (2010).
**Drivers and enablers**

Future satellite communications may be enabled by continuing advances in a wide range of science, technology and engineering disciplines. This includes advances in laser and optical systems; quantum science and encryption; energy generation, storage and transmission; antennae, transmitters and receivers; cybersecurity; satellite design (e.g. smallsats); and integrating new materials such as graphene and metamaterials as the basis for telecommunications hardware to transmit and receive signals in the Tremendous High Frequency (THF) range.451

Innovations in launch vehicle designs, including reusable rockets, have provided incentives for advancing new models for delivery of telecommunications services, including LEO-based services. The continuing development of reusable launch systems may further incentivise the growth in smallsat telecommunications, given the possibility of delivering large quantities of smallsats in a single launch.452

Current and future growth in global demand for various telecommunications services (with improved coverage, capacity, bandwidth, redundancy and security, and reduced latency) provides a strong business case for continuing investment in this field by government, military and commercial organisations. The size of the existing and potential global market, as well as the critical role played by SATCOM in a wide range of other markets, critical services and the Internet of Things, all provide a strong impetus to continuing innovation in this field, as well as competition between different firms and approaches.

**Potential barriers and challenges to implementation**

While global broadband coverage is a key ambition of future space-based telecommunications markets, several significant challenges persist.

Ensuring coverage and connectivity for remote and rural areas, including the polar regions, faces its own set of challenges including underdeveloped investment models, the demographic profile of highly remote regions (leading to an uncertain long-term market value for many services), and harsh environmental conditions that limit the potential for realising large-scale infrastructure projects.453

Depending on the perspective, regulatory challenges include the limiting effects of increased government regulations for market growth or, on the other hand, an insufficiently robust regulatory framework for services such as smallsat constellations-based communications. There are particular concerns about the need for improved spectrum management to prevent EM ‘fratricide’ between satellites, and about the risks posed by the launch and operation of mega-constellations of smallsats in LEO. These increase the potential for debris, potentially endangering the transit of crewed missions to higher orbits, as well as increasing the risk of cascading collisions, leading to the Kessler syndrome.

Lack of funding may also present a barrier for inclusion of start-up companies in the telecommunications market, given the high barriers to entry and fierce competition from more established players.454

The growing reliance of governments, economies and societies on SATCOM (which is only expected to increase with the adoption of IoT technologies) also raises the risk that hostile state or non-state action might seek to subvert, disrupt or damage space- or ground-based communications infrastructure (e.g. spacecraft, satellites, payloads or key ground and downlink installations, such as at Svalbard). This threat is increasing given the proliferation of counter-space capabilities, whether involving kinetic, cyber or electronic means of attack, and requires effective SSA/SST, deterrence and other measures to ensure the resilience and security of space-enabled telecommunications.

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452 Pallone (2018).
453 Catapult Satellite Applications (2017u).
454 Catapult Satellite Applications (2017o).
### Summary of potential impacts and implications for the space economy

<table>
<thead>
<tr>
<th>Category</th>
<th>Impact</th>
</tr>
</thead>
</table>
| **Prosperity**                    | • Significant market growth opportunities in the next 10–15 years in the telecommunications sector, including novel products and services, e.g. satellite broadband.  
• Improved satellite communications coverage, capacity and capabilities as basis for various downstream markets (e.g. telemedicine, telework, connected and autonomous vehicles, finance, gaming, entertainment), as well as space missions.  
• Enabler for adoption of Internet of Things devices across different industries (e.g. agriculture, mining, manufacturing) and in consumer markets (e.g. smart homes, wearables).  
• Increased integration of remote communities and developing economies into the global digital economy, boosting growth.  
• Increased scope for remote working and provision of services (e.g. telehealth, e-learning), reshaping business practices.  
• Increased productivity through access to data, tools and communications even while in transit in a vehicle. |
| **Environment & net-zero economy**| • Improved connectivity as driver for reduced transport emissions (e.g. due to shift towards telecommuting).  
• Improved connectivity for networked sensors used in climate and environmental monitoring.  
• Provision of satellite communications services for humanitarian aid and disaster relief operations in climate-affected regions.  
• Environmental benefits of long-term relocation of data centres to solar-powered installations in space. |
| **National security & defence**   | • Improved reach and resilience of telecommunications for security and defence, including military SATCOM.  
• Opportunities arising from new technologies – e.g. quantum – to improve security of encrypted military communications.  
• Increasing importance of satellite communications to joint, all-domain command, and command for operations.  
• Increasing requirement to secure satellite communication infrastructure against accidental damage (e.g. collisions) or purposeful attack (cyber, electronic or kinetic). |
| **Science & discovery**           | • Provision of communications for deep-space exploration and space-based networked sensors for scientific purposes.  
• Improved connectivity for research organisations gathering and sharing data from terrestrial or space sources.  
• New research opportunities relating to data fusion, Big Data analytics and AI/ML, facilitated by improved communication. |
| **International collaboration**   | • Improved communications provision for international collaborative space programmes.  
• Increased need for ITU and other national or international organisations to shape regulation, norms and standards for the future of telecommunications.  
• Improved global connectivity and cross-border exchange of ideas, products and services, including in remote areas. |
Annex O. Transport

Transport

Definition

This cluster comprises all those activities in or enabled by space that are focused on the movement of people or goods from one location to another, typically by means of a vehicle, and on the provision of related services to ensure the safe and efficient function of transport networks.

Relation to other clusters: For those future space applications relating to the task of integrating means of transportation with the broader organisation of supply chains, see Annex K on 'Logistics'.

Description of case study

Future uses of space for transport extend to intra-space transportation and services, as well as the use of space-based SATCOM, PNT and other services to support transport systems on Earth.

Space services have wide-ranging applications as enablers for the transport sector, offering improvements in efficiency (e.g. through route optimisation), safety (e.g. through providing connectivity for safety-critical services and providing enhanced Health and Safety monitoring), and connectivity for networked systems and future transport models (e.g. smart cities and user models such as ride-sharing).

There are also significant opportunities arising from the use of space-based services in support of UK Government targets to cut emissions across the transport sector to meet the 'net zero' target for 2050 (see Annex B on 'Climate and environmental protection') and support growth of a green economy.

Demand for novel forms of transportation within space will be shaped by the evolution of the wider space ecosystem (e.g. space habitats, factories, resource extraction sites etc.) beyond 2030, but terrestrial transport systems represent a significant near and medium-term growth area (e.g. driven by ongoing shifts towards autonomous vehicles, electrification and smart transport solutions).

Beyond its dependency on increased demand from space users, in-space transportation faces several technological barriers that will need to be overcome to realise some of the more ambitious visions for new modes (e.g. magnetic space trains, nano-ships, interstellar probes). Challenges to implementation of new space-enabled solutions for terrestrial transport include uncertainties regarding the performance of certain technologies, as well as a lack of end user awareness or trust of their utility in this sector.
### Relevant use cases

#### Space markets

- **Intra-space transportation**: Future intra-space transportation may draw on a range of specialist vehicles, including lunar and Martian shuttles and rovers for planetary transport of personnel and goods; or magnetic space trains, solar sails and nano-ships for interplanetary and interstellar transport.\(^\text{455}\)

- **Space traffic management**: The presence of an increasing number of satellites and expired/inactive spacecraft in space incentivises development of robust space traffic management services aimed at avoiding collisions, accidents and conflicts. Such services build on but are distinct from SSA/SST and require not just technical but also regulatory provisions, including agreed standards on safe behaviour in space, RF spectrum management, and a resilient and common communications architecture. National and international ‘traffic police’ efforts may be directed at improved tracking, prediction, identification, management and redirection of space objects, as well as information sharing among operators.\(^\text{456}\)

#### Hybrid markets

- **Safety-critical services**: Space-based services including SATCOM may facilitate safety-critical services for both space and terrestrial transport systems, including by enabling emergency communications and alerts, trajectory management, Sense and Avoid, live streaming Search and Rescue, and System-Wide Information Management.\(^\text{457}\)

- **Space services for real-time fleet, vehicle and sub-system health monitoring**: Space-based services may deliver operational improvements to space and terrestrial transport systems, including through more real-time health monitoring of fleets, vehicles and sub-systems (e.g. engines) to optimise performance and enable predictive maintenance.\(^\text{458}\)

- **Space services for crew training, welfare and remote monitoring of Health and Safety**: SATCOM and 5G/6G connectivity may enable improved crew Health and Safety solutions, including through remote monitoring of health parameters (e.g. sleep patterns and stress levels) and integration with crew tracking data.\(^\text{459}\)

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455 Wenz (2017); Planetary Society (n.d.).
456 Morin (2019).
457 Catapult Satellite Applications (2017c).
458 Catapult Satellite Applications (2017c).
459 Catapult Satellite Applications (2017d).
• **Satellite-enabled vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication**: SATCOM may also enable V2V and V2I communications, defined as ‘the transmission of data, between motor vehicles themselves [or between vehicles and other infrastructure], and/or via a central control system, through a wireless medium’. Satellite V2V and V2I communication serves to improve road safety, reduce risks of collisions and road accidents, encourage use of autonomous vehicles and facilitate creation of smart cities.

• **Connectivity for smart cities and infrastructure**: Smart cities represent concepts of future cities integrating a range of technologies to ‘improve a city’s efficiency, optimisation, predictability, convenience and security’. Space services may provide more robust communications between sensor devices and smart-city platforms, as well as encouraging multi-modal integration (e.g. seamless integration of ticketing and timetables between car, bus, metro and rail networks).

• **Connectivity for autonomous vehicles (in all domains)**: Satellite connectivity and positioning services may enable the operation of connected and autonomous vehicles (CAVs) in the space, air, maritime and land domains, reducing the requirement for human drivers/pilots.

• **Connectivity to enable new vehicle ownership and use models**: Space-based technologies may have applications for new vehicle ownership and use models, including ensuring connectivity for ride-sharing apps and self-owning CAVs, and enabling a transition to ‘Mobility as a Service’ (MaaS).

• **Next-generation PNT services**: Next-generation PNT may bring a range of benefits, including improved navigation and transport safety through the provision of support to emergency services and road traffic management.

• **Intelligent Transport Systems and route, speed and transport service optimisation to reduce congestion**: Space-based broadband and PNT may enable enhanced e-navigation and route optimisation for all domains. This may contribute to increased safety, resource and fuel optimisation and reduced risk of congestion in transport networks.

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460 Catapult Satellite Applications (2017b).
461 Rohr et al. (2016).
462 Catapult Satellite Applications (2017k).
463 Catapult Satellite Applications (2017b).
464 Rohr et al. (2016).
466 Catapult Satellite Applications (2017w).
467 Catapult Satellite Applications (2017d).
<table>
<thead>
<tr>
<th>Terrestrial markets</th>
</tr>
</thead>
<tbody>
<tr>
<td>• <strong>Broadband-to-vehicles to increase user productivity and entertainment in-transit.</strong> Space-based services may provide improved passenger services and connectivity for work or entertainment purposes (e.g. In-Flight WiFi, Voice-over-IP and multi-media streaming), boosting productivity in-transit.⁴⁶⁸</td>
</tr>
<tr>
<td>• <strong>Air traffic management:</strong> Space-based EO (e.g. radar, lidar), SATCOM and PNT may all be utilised to enhance future terrestrial air traffic management, particularly in relation to more robust systems and global sensor coverage, more reliable prediction and efficient coordination of scheduling.⁴⁶⁹</td>
</tr>
<tr>
<td>• <strong>Maritime traffic management and maritime surveillance:</strong> Similarly, space-based services may be utilised in maritime traffic management, as well as monitoring and surveillance of maritime traffic. This may assist in maritime security as well as coordination of maritime Search and Rescue operations.⁴⁷⁰</td>
</tr>
<tr>
<td>• <strong>Rail traffic management and track monitoring:</strong> Space-based services for rail networks may include improved rail traffic planning and real-time maintenance support, including preventative track maintenance using embedded sensors.⁴⁷¹</td>
</tr>
<tr>
<td>• <strong>Road traffic management:</strong> EO, SATCOM and PNT may perform various future roles for road traffic management, including monitoring of road networks and emissions, detecting degradation of road infrastructure (e.g. bridges) and facilitating emergency services and repair crews.⁴⁷²</td>
</tr>
<tr>
<td>• <strong>Road pricing and congestion charging:</strong> Low-cost space-enabled communications for roadside and vehicle-mounted devices may facilitate improved, flexible and more resilient road pricing and congestion charging systems.⁴⁷³</td>
</tr>
<tr>
<td>• <strong>Usage-based insurance schemes and driver monitoring:</strong> Low-cost SATCOM and PNT services may facilitate improved, user-needs-tailored insurance services (e.g. pay-as-you-go insurance) and driver training/monitoring (e.g. telematics).⁴⁷⁴</td>
</tr>
</tbody>
</table>

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⁴⁶⁸ Catapult Satellite Applications (2017c).
⁴⁶⁹ NASA (2019a).
⁴⁷¹ Catapult Satellite Applications (2017v).
⁴⁷² Catapult Satellite Applications (2017w).
⁴⁷³ Catapult Satellite Applications (2017w).
⁴⁷⁴ Catapult Satellite Applications (2017w).
Main actors

Future space-based and space-enabled transportation markets may engage a wide variety of stakeholders, including:

- Transport and urban planning and management services, including national and local authorities.
- Commercial and industry stakeholders, including UK satellite operators and providers of mobile coverage (e.g. Inmarsat, Avanti, UK offices of Intelsat and SES, and others).
- Automotive, aerospace and shipping manufacturers and operators.
- Insurance and finance companies.
- Logistics and freight providers.
- Emergency services and maintenance teams.
- Research and academic institutions as important stakeholders in the future of space transportation, as new methods and mission concepts are developed.
- Passengers and representative groups (e.g. Transport Focus watchdog in the UK).

There are also important links between the transport sector and stakeholders involved in promoting GDP growth and prosperity, as well as fulfilment of UNFCCC and national goals to reduce vehicle emissions (both to combat climate change and reduce air and water pollution) out to 2050.

Within the UK, ‘Intelligent Transport’ is also one of the stated focus areas of the Satellite Applications Catapult, while ‘Universal traffic management and Beyond Visual Line of Sight (BVLOS) flight’ is named as a specific area of interest within another focus area for ‘Emerging Technologies’.

Value proposition to end users

<table>
<thead>
<tr>
<th>Government (civil)</th>
<th>Reduced risk of collisions and damage to national space-based assets; greater resilience of space-based services.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Support to realisation of government ambitions for shifts towards smart infrastructure/cities, electrification and CAVs to optimise use of resources as well as meet emissions targets.</td>
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<tr>
<td></td>
<td>Development of novel Health and Safety solutions, along with support for emergency services and Search and Rescue.</td>
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<tr>
<td></td>
<td>Enhanced resilience and efficiency of transport infrastructure through real-time monitoring and predictive maintenance.</td>
</tr>
<tr>
<td></td>
<td>Greater efficiency of traffic controls, including use of congestion- and road-charging to secure revenue.</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Government (military)</th>
<th>Space traffic management could avoid potential incidents and unintended crisis escalation, or Kessler syndrome in space.</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Support to improved SSA/SST capabilities, as well as air and maritime traffic monitoring for security purposes.</td>
</tr>
<tr>
<td></td>
<td>Improvements in Search and Rescue capabilities in the space, land, air and maritime domains.</td>
</tr>
</tbody>
</table>

475 Catapult Satellite Applications (2020b).
476 Catapult Satellite Applications (2020b).
477 Catapult Satellite Applications (2017w).
Civil (commercial)

- Reduced risk of damage to commercial space objects through provision of robust space-traffic management.
- Enhanced safety and protection of crews/passengers and improved staff welfare and well-being.
- Increased market opportunities to provide passenger services, e.g. connectivity for entertainment.
- Avoidance of significant reputational risks and financial liabilities associated with deadly crashes and other accidents.

Civil (other)

- Generation of new data and insights for transport-related research and development efforts.
- Support for passenger advocacy groups and watchdogs in shaping government and commercial transport policies.

Consumers

- Improving safety of transport across all domains.
- Facilitating new ownership models and travel affordability.
- Facilitating reduced journey times.
- Improving passenger services to increase productivity and enjoyment while in-transit.

Estimate of timeframes

Future growth in the demand for intra-space transportation services will be dependent on how quickly and on what scale current ambitions for other space-based activities (e.g. energy, manufacturing, habitation) come to fruition out to 2050, but it is likely that demand will remain low in the 2020s and then grow in the 2030s and 2040s as more long-term and complex space operations come online.

The initial focus is likely to be on the Moon (e.g. given Chinese ambitions to begin construction of a permanent lunar base from 2035) and creation of an integrated ‘cis-lunar transportation system’ involving spacecraft, waystations, landers and rovers.\(^{478}\) Into the 2040s, Mars is likely to become a growing area of interest as crewed and uncrewed missions to the planet’s surface increase in scope, duration and frequency, potentially to include the establishment of permanent settlements.

Large-scale interplanetary and even interstellar transportation markets represent a more long-term outlook. For example, NASA’s interstellar nano-ship mission-concept is aimed at realisation before 2069.\(^{479}\) Startram’s concept for an electromagnetic intra-space train system would, similarly, require 20 years for completion following initiation of construction.\(^{480}\)

Looking to terrestrial markets, space applications in areas such as traffic management – especially international air traffic management – are projected to mature out to 2030,\(^{481}\) while smart cities, infrastructure and more large-scale adoption of CAVs is expected towards 2040,\(^{482}\) with 10 per cent of road vehicles expected to be fully automated by 2030 and rapid growth thereafter as technology improves, old vehicles are replaced and public attitudes evolve.\(^{483}\)

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\(^{478}\) Dorminey (2016).

\(^{479}\) Wenz (2017).

\(^{480}\) Farkas (2016).

\(^{481}\) OECD (2004).

\(^{482}\) Rohr et al. (2016).

\(^{483}\) Reese (2020).
Drivers and enablers

Future intra-space transportation markets will be enabled by significant technological advances in propulsion technologies (e.g. improved chemical and ion engines, as well as experimentation with new approaches, e.g. fusion), energy generation and storage, materials, AI/ML and autonomy. Alternative technologies such as solar sails riding laser beams could also augment existing propulsion and acceleration capabilities for future interplanetary or even interstellar transport.\(^{484}\)

The use of space-based technologies for hybrid and terrestrial transport solutions will be shaped by both technical and non-technical enablers. The number of EO satellite constellations should enable greater availability of networks and coverage for remote and urban areas, which may incentivise further adoption of space-based services in the transportation sector, including for traffic management.\(^{485}\)

The continuing drive to improve safety, reduce congestion, modernise infrastructure and maximise the contributions of the transport sector to tackle climate change and air and water pollution out to 2050 all provide a strong logic for continuing investment in space applications that align with these goals.

The size of the global market for air, road, rail and marine transportation and the expected levels of future growth (e.g. the UK’s Department for Transport predicts road traffic will grow between 19 per cent and 55 per cent from 2010 out to 2040) provide both commercial opportunities as well as pressure for new policy and regulatory interventions to ensure the efficient function of global, national and local networks.\(^{486}\)

Potential barriers and challenges to implementation

As described above, the requirement for new propulsion systems and other technological advances indicate that future intra-space transportation may be limited in the future if innovation in these areas proves more difficult than the more ambitious projections anticipate.

There are also important non-technical barriers for space transportation and related services, including the need to develop and enforce international norms and standards, for example in relation to space traffic management, spacecraft and satellite operations, liability, and attribution of collisions.\(^{487}\)

The future use of space-enabled hybrid and terrestrial transportation services also faces several challenges. Increased connectivity and reliance on SATCOM and other services may increase the vulnerability of transport services to disruption through cyber or electronic attacks, including spoofing, jamming and ‘meaconing’.\(^{488}\) Additional barriers to the further adoption of space-based services for terrestrial transport networks include increased energy requirements and technical challenges with the performance of networked and autonomous systems in complex and cluttered urban environments.\(^{489}\)

Lack of awareness among authorities concerning the benefits of space-based services – such as EO – and a culture of risk aversion may also limit the adoption of such services in traffic management and other transportation functions.\(^{490}\) Existing research points out, for example, that ‘the provision of EO services is seen to be the remit of either military or highly secure and/or high value assets’, even if the relevance of SATCOM and especially PNT to transport users is more widely understood.\(^{491}\)

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484 Planetary Society (n.d.).
485 Catapult Satellite Applications (2017w).
486 Rohr et al. (2016).
487 Morin (2019).
488 ‘Mecaconing’ refers to the interception and rebroadcasting of navigational aids (e.g. GPS signals) to confuse navigation.
489 Catapult Satellite Applications (2017w).
490 Catapult Satellite Applications (2017v).
491 Catapult Satellite Applications (2017w).
Uncertainties concerning the performance of space-based technologies and services, as well as their perception as high-cost solutions, further limit the incentives for adoption by potential end users, while the uptake of related technologies — such as smart cities and CAVs — will also be dependent on evolving public attitudes (e.g. concerns around safety, privacy and data security).

**Summary of potential impacts and implications for the space economy**

### Prosperity
- Initial investment into new in-space transportation technologies may lead to development of inexpensive transport methods (e.g. solar sailing, electromagnetic propulsion) that facilitate other economic activities (e.g. space-based manufacturing).
- More robust and resilient connectivity for smart transport solutions brings extensive economic and social benefits. The CAVs market alone is projected to contribute £51bn per year in social and economic benefits by 2030.
- Reducing congestion and improving the efficiency and competitiveness of travel, freight and logistics, benefitting the retail, e-commerce, tourism and manufacturing sectors.
- Increased monitoring of transport infrastructure can facilitate more targeted and predictive maintenance and deliver greater returns for initial infrastructure investment.
- Increased passenger productivity while in-transit may result in shifting patterns of business travel, as well as GDP growth.
- Increased granularity of information on vehicle and infrastructure use may support more efficient road pricing as well as new financial and insurance products.

### Environment & net-zero economy
- Contribution to fulfilment of UNFCCC climate targets and UK Government goals for a carbon net-zero economy by 2050.
- Route optimisation and space-enabled traffic management may reduce the environmental impacts of transport networks, including by reducing fuel usage and CO₂ emissions.
- Support to ongoing shift towards CAVs and electrification.
- Support to development of smart infrastructure, including embedded sensors for monitoring air and water pollution.

### National security & defence
- Reduced risk of in-space collisions and accidents, preventing unintended escalation of a crisis or the Kessler syndrome.
- Support to use of autonomous systems in unsegregated airspace or waters for military purposes.
- Improved air and maritime security through enhanced situational awareness and traffic management.
- Increasing need to secure space-based infrastructure as CNI to prevent physical, cyber or electronic attacks that could compromise both space and terrestrial transport systems.

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492 Catapult Satellite Applications (2017w).
493 Catapult Satellite Applications (2017x).
494 NASA (2019a).
### Science & discovery

- Development of new in-space transportation markets may advance space exploration, including both within the Solar System as well as increasingly looking to interstellar missions.
- Enhanced data and insights on terrestrial transportation systems provide opportunities for academic research, including in relation to economic and environmental impact.

### International collaboration

- Impetus for international collaboration on space traffic management, including through established information-sharing mechanisms, status reports and collision alerts.\(^{495}\)
- Impetus for international collaboration on improving regulatory and legal frameworks for space traffic and debris management, including development of international protocols, norms and standards.\(^{496}\)
- Potential for deepening cooperation on air and maritime traffic management and environmental monitoring.
- Potential for deepening transnational ties through travel, tourism and logistics, supporting global trade.

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\(^{495}\) Morin (2019).
\(^{496}\) Morin (2019).
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