WIPO Technology Trends
Technical Annex

Future of Transportation in Space

WIPO

World Intellectual Property Organization
34, chemin des Colombettes, P.O. Box 18
CH-1211 Geneva 20, Switzerland

wipo.int

DOI: 10.34667/tind.57970

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Introduction to space transportation

This technical annex to the WIPO Technology Trends Report on the Future of Transportation provides an in-depth examination of the technological landscape within the domain of land transportation. It is a deep dive analysis of global patenting trends in land transportation affording comprehensive insights into those innovations shaping the future of road and rail transport systems. Full details on the research methodology and different patent indicators used can be found in the Appendix to the report.

By exploring patent data, this annex identifies emerging technologies, key players and evolving trends impacting the development and enhancement of infrastructure, vehicle advancements, smart systems and sustainable transport solutions. The analysis extends to the interconnections between these technologies, assessing their potential to revolutionize mobility, improve efficiency and drive economic and environmental sustainability across the transportation sector.

This annex serves as a valuable resource for those stakeholders – including policymakers, industry leaders, researchers and innovators – seeking to understand the trajectory of technological advancements and their implications for the future of land transportation.

Figure D1 Exploring the main findings of the WIPO Technology Trends report on the Future of Transportation

Future of Transportation

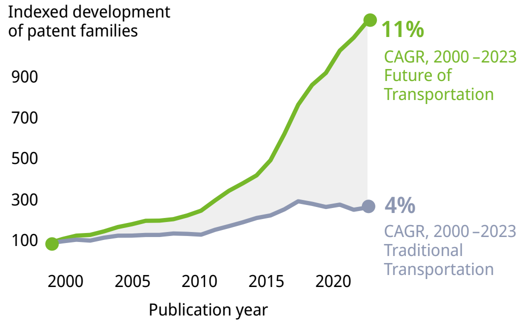
1.1M+

Inventions (Patent families) published, 2000–2023

11% ⬆

The number of patents related to the future of transportation has grown at a compound annual growth rate (CAGR) of nearly 11%.

In comparison, patents in traditional transportation have grown at a rate of only **4%** over the same period.



Two megatrends and four technology trends

Sustainability

Sustainable Propulsion is driving the Sustainability megatrend.

Digitalization

Communication and Security is driving the Digitalization megatrend.

Sustainable Propulsion	Automation and Circularity	Communication and Security	Human–Machine Interface
98%	26%	78%	15%
Proportion in Sustainability megatrend	Proportion in Sustainability megatrend	Proportion in Digitalization megatrend	Proportion in Digitalization megatrend

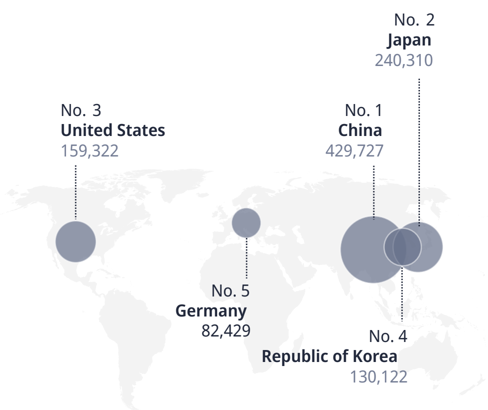
Modes of transportation

Most patents related to Land transportation

Land	Sea	Air	Space
82%	4%	12%	7%
Proportion in future of transportation	Proportion in future of transportation	Proportion in future of transportation	Proportion in future of transportation

Leading locations

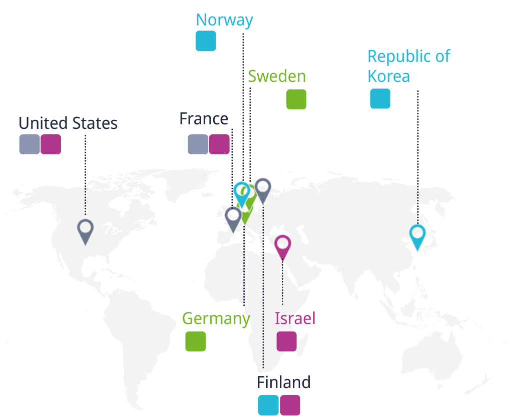
Number of patent families invented in the location



Specialized locations

Notable locations with a high Relative Specialization Index

Land Sea Air Space



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Overview of space transportation

Space transportation involves the movement of people, goods and satellites beyond the Earth's atmosphere, primarily using rockets and spacecraft. [1] It encompasses various vehicle types, including crewed spacecraft, cargo spacecraft and satellites, and relies on infrastructure such as launch pads, spaceports and mission control centers. [2] This mode of transportation has evolved from early experimental launches to modern, technologically advanced systems, playing a crucial role in scientific exploration, global communication and economic activities.

Space transportation is indispensable for the overall transportation system owing to its unique ability to operate beyond Earth's atmosphere, making it a vital link in global communication networks, satellite-based services and space exploration. [3] Unlike air and land transport, which are limited to the Earth's surface, space transport can directly connect distant points in space, fostering global connectivity and scientific advancement. This makes it essential for providing satellite deployment, space station resupply and space tourism, which are critical for both scientific research and commercial endeavors. [4] Thus, space transport often acts as a facilitator for other modes of transportation, ensuring the deployment and maintenance of satellites that support global positioning systems (GPS), weather forecasting and telecommunications. [5] For instance, communication satellites launched into orbit by rockets enable global broadcasting and internet services. Similarly, scientific instruments deployed in space rely on space transportation for their placement and operation.

Space transportation plays a crucial role in global communication, scientific research and economic development. According to McKinsey scenario planning, it is anticipated that there will be 27,000 active satellites in orbit by the end of 2030, an almost four-fold increase from today. In a high-demand scenario, in which nearly all proposed constellations materialize, we would expect to see more than 65,000 satellites, including many heavier ones, in orbit by 2030. [6] Such predicted growth highlights an increasing demand for satellite services, driven by advancements in technology and the need for global connectivity. Regions like North America and Europe will see significant investments in satellite infrastructure, while emerging markets in Asia and Africa will experience rapid growth in satellite deployment. [7]

Space transport's share of CO_2 emissions is relatively small compared to other transportation modes, but is still expected to grow under current policies. In 2020, space transport accounted for a fraction of global CO_2 emissions. However, by 2050, under the Current Ambition scenario, [8] emissions from space transport activities will increase as more launches occur in support of growing satellite networks and space exploration missions. Even under the High Ambition scenario, where total emissions are reduced significantly, space transport emissions will still be a focus for sustainability efforts.

Despite a growth in demand, efforts to decarbonize the space transport sector are critical for reducing emissions and achieving sustainable space exploration. This includes adopting Sustainable Propulsion technologies, improving launch efficiency and implementing policies that encourage the use of cleaner technologies. Such measures will help create a more sustainable and efficient space transportation system, capable of meeting future demands, while minimizing environmental impacts. [9]

1 Britannica (2024). Space exploration. Available at: www.britannica.com/science/space-explorationwww.britannica.com/science/space-exploration.
2 FAA (2004). Space Vehicle Operators Concept of Operations: A Vision to Transform Ground and Launch Operations. Federal Aviation Administration. Available at: www.faa.gov/about/office_org/headquarters_offices/ast/media/Space_Vehicle_Operators_CONOPS_v18.pdf.
3 ESA (2005). The Impact of Space Activities upon Society. European Space Agency. Available at: www.esa.int/esapub/br/br237/br237.pdfwww.esa.int/esapub/br/br237/br237.pdf.
4 Aglietti, G. S. (2020). Current challenges and opportunities for space technologies. Frontiers in Space Technologies, 1, 1.
5 Kodheli, O., E. Lagunas, N. Maturo, S. K. Sharma, B. Shankar, J. F. M. Montoya et al. (2020). Satellite communications in the new space era: A survey and future challenges. IEEE Communications Surveys and Tutorials, 23(1), 70–109.
6 McKinsey (2023). Space launch: Are we heading for oversupply or a shortfall? McKinsey & Company. Available at: www.mckinsey.com/industries/aerospace-and-defense/our-insights/space-launch-are-we-heading-for-oversupply-or-a-shortfall.
7 ADB (2021). Digital Connectivity and Low Earth Orbit Satellite Constellations: Opportunities for Asia and the Pacific. Asian Development Bank. Available at: www.unapcict.org/sites/default/files/2021-05/Digital%20Connectivity%20and%20Low%20Earth%20Orbit%20Satellite%20Constellations%20Opportunities%20for%20Asia%20and%20the%20Pacific.pdf.
8 OECD. Transport. Organisation for Economic Co-operation and Development. Available at: www.oecd-ilibrary.org/transport/carbon-dioxide-emissions-under-the-current-ambition-and-high-ambition-scenarios_266cc8a7-en.
9 BCG (2024). Regulating the next generation of satellites. Boston Consulting Group. Available at: www.bcg.com/publications/2024/regulating-the-next-generation-of-satellites.

Sustainability and digitalization are megatrends that play a vital role in transforming the future of space transport. The focus on sustainability drives innovation toward reducing CO_2 emissions and promoting greener practices. Meanwhile, digitalization enhances operational efficiency through advancements in technology and data analytics, making space transportation systems smarter and more adaptive to future challenges. According to analysis by *The Guardian* newspaper, the space transportation sector, while still currently a small emitter, has significant potential for adopting sustainable practices to minimize its environmental footprint, especially when space transportation as an industry is set to increase. [10]

The International Astronautical Federation (IAF) has highlighted the need for ambitious policies to achieve significant reductions in space transport emissions, projecting that CO_2 emissions from space activities could be minimized, if the right measures are in place. The European Space Agency (ESA) also emphasizes the potential of accelerating the transition to Sustainable Propulsion technologies and implementing efficiency technologies for both launch vehicles and spacecraft, so as to significantly reduce emissions by 46% until 2030. [11] Such commitments reflect a concerted effort by global organizations to address the climate impact of the space transportation sector.

Digitalization is revolutionizing the space transportation sector, by driving significant advancements in efficiency, safety and mission success rates. A key driver is the substantial increase in investment into technology, particularly post the COVID-19 pandemic, as companies and agencies allocate more resources to digital and tech initiatives. This surge in spending underscores the strategic importance of digital transformation in maintaining a competitive edge. Additionally, smart mission planning and execution tools optimize resources, reduce waste and improve logistical efficiency.

Sustainable Propulsion technologies are transforming both crewed and uncrewed space transportation:

- **Sustainable propulsion systems** are a cornerstone of sustainable space transportation, offering significant reductions in CO_2 emissions compared to traditional chemical rockets. Sustainable Propulsion technologies are transforming space transportation. Low-carbon propulsion, including hybrid rocket engines and biofuels, aims to reduce greenhouse gas emissions from launches. [12]
- **Battery-based spacecraft** represent a promising solution for short missions and orbital maneuvers, offering zero tailpipe emissions and lower operating costs. Advanced batteries, such as lithium-ion and solid-state, offer efficient energy storage for spacecraft systems. [13] Such spacecraft are powered by advanced battery technologies, which are continually improving in terms of energy density and charging times. This technology is crucial for reducing emissions in sectors where full electrification might not yet be practical, because of range limitations.
- **Hydrogen-powered rockets** are emerging as a potential solution for long-duration missions and heavy-duty applications. Hydrogen can be used in fuel cells to generate electricity or burned in modified rocket engines. This technology offers the potential for zero-emission launches, with water vapor being the only byproduct. [14]

Automation and Circularity technologies are reshaping space transportation, by promoting efficient material use, smart production and enhanced recycling practices.

- **Efficient material use** is a key component of the circular economy, aiming to minimize waste and maximize resource efficiency. This involves adopting lightweight materials, utilizing advanced manufacturing techniques to reduce material waste and designing spacecraft

10 The Guardian (2021). How the billionaire space race could be one giant leap for pollution. Available at: https://www.theguardian.com/science/2021/jul/19/billionaires-space-tourism-environment-emissions www.theguardian.com/science/2021/jul/19/billionaires-space-tourism-environment-emissions.

11 IAF (2023). IAF Highlights 2023. International Astronautical Federation. Available at: https://www.iafastro.org/assets/files/publications/highlights/iaf-highlights-2023-web.pdf www.iafastro.org/assets/files/publications/highlights/iaf-highlights-2023-web.pdf.

12 Suhasaria, V., B. Arora, N. Deshmukh, S. Das and A. K. Mishra (2022). Role of sustainable energy for future aerospace application: Comprehensive review. International Journal of All Research Education and Scientific Methods (IJARESM), 10(12), 1477–1494.

13 Pathak, A. D., S. Saha, V. K. Bharti, M. M. Gaikwad and C. S. Sharma (2023). A review on battery technology for space application. Journal of Energy Storage, 61, 106792.

14 Airforce Technology (2023). Environmental sustainability: Who are the leaders in H2-powered rockets for the aerospace and defense industry? Available at: www.airforce-technology.com/data-insights/innovators-es-h2-powered-rockets-aerospace-and-defense/?cf-view.

for disassembly and recycling. [15] Such practices ensure that materials are used optimally throughout the product lifecycle, reducing environmental impact and conserving resources.
- **Smart production and robotics** are together transforming manufacturing processes, by enhancing efficiency, precision and flexibility. Advances in Industry 4.0 technologies, such as internet of things (IoT), machine learning and cyber-physical systems, are enabling autonomous production lines that can adapt to real-time data and optimize operations. [16] Thus, smart production systems can significantly reduce waste, improve product quality and enable predictive maintenance, thereby extending the lifespan of machinery and equipment. Robotics plays a crucial role in automating repetitive tasks, improving accuracy and reducing human error, all of which contribute to a more sustainable manufacturing process.
- **Recycling** is a fundamental aspect of the circular economy, aiming to recover valuable materials from end-of-life products and reintroduce them back into the production cycle. The importance of intelligent automation in enhancing recycling processes, such as sorting and processing recyclables more efficiently, is growing. Innovative technologies like AI and robotics are improving the accuracy and efficiency of recycling operations, ensuring that more materials are recovered and reused. [17]

Communication and Security technologies are paving the way for a new era of space transportation:

- **Advanced mission control systems** are becoming increasingly essential for both crewed and uncrewed missions. These systems leverage real-time data, advanced routing algorithms and AI to optimize mission planning, reduce delays and improve fuel efficiency. [18] A research survey emphasizes that the integration of AI into mission control systems is transforming mission planning, by predicting space weather patterns and suggesting alternative routes in real-time. [19]
- **Device-to-device technology** enhances communication between various systems and devices within the space transportation ecosystem. This technology enables seamless data exchange between spacecraft, ground control, satellites and mission-critical devices, improving operational efficiency and safety. [20] By facilitating real-time information sharing, device-to-device communication helps in proactive maintenance, better mission planning and more efficient operations.
- The adoption of **cloud computing** and **low-latency internet** is revolutionizing how data are managed and utilized in space transportation. Cloud platforms enable the collection, storage and analysis of vast amounts of data from connected spacecraft and infrastructure. According to the Boston Consulting Group (BCG), low-latency internet, particularly through satellite-based networks, facilitates real-time communication between spacecraft and mission control systems. [21]
- As space transportation becomes more digitalized, **cybersecurity** has become of paramount concern. Protecting space networks from cyber threats is essential to assuring the safety and reliability of both crewed and uncrewed missions. [22] The rise of digital technologies has made space systems more vulnerable to cyberattacks, emphasizing the need for robust cybersecurity measures. Such measures include encryption, secure communication protocols and continuous monitoring to detect and mitigate potential threats. [23]

Advanced **Human-Machine Interface (HMI) technologies** are driving the evolution of space transportation, by making interactions more intuitive, secure and responsive, thereby improving operational efficiency and user experience.

15 European Commission (2024). Horizon Europe: Work Programme 2023–2025 – Digital, Industry and Space. Available at: https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/horizon/wp-call/2023-2024/wp-7-digital-industry-and-space_horizon-2023-2024_en.pdf.
16 UK Space Agency (2022). Space Exploration: Technology Roadmap. Available at: https://assets.publishing.service.gov.uk/media/64ff28391886eb00139770ef/Space_Exploration_Technology_Roadmap_v2.pdf.
17 Smith, J. (2020). The impact of artificial intelligence on recycling processes. Journal of Recycling and Waste Management, 25(2), 57–71.
18 Shah, V. (2024). Next-generation space exploration: AI-enhanced autonomous navigation systems. Journal Environmental Sciences and Technology, 3(1), 47–64.
19 Russo, A. and G. Lax (2022). Using artificial intelligence for space challenges: A survey. Applied Sciences, 12(10), 5106.
20 Monzon Baeza, V., F. Ortiz, S. Herrero Garcia and E. Lagunas (2022). Enhanced communications on satellite-based IoT systems to support maritime transportation services. Sensors, 22(17), 6450.
21 BCG (2024). Regulating the next generation of satellites. Boston Consulting Group. Available at: www.bcg.com/publications/2024/regulating-the-next-generation-of-satellites.
22 DIA (2022). Challenges to Security in Space: Space Reliance in an Era of Competition and Expansion. Defense Intelligence Agency. Available at: www.dia.mil/Portals/110/Documents/News/Military_Power_Publications/Challenges_Security_Space_2022.pdf.
23 Diro, A., S. Kaisar, A. V. Vasilakos, A. Anwar, A. Nasirian and G. Olani (2024). Anomaly detection for space information networks: A survey of challenges, techniques, and future directions. Computers and Security, 139, 103705.

- **Extended reality (XR) technologies**, including virtual reality (VR), augmented reality (AR) and mixed reality (MR), are significantly enhancing HMIs, by providing immersive and interactive experiences. These technologies are particularly beneficial in space for training, maintenance and mission planning, offering real-time data overlays and interactive simulations to improve operational efficiency and decision-making. [24]
- **Speech recognition technology** is transforming HMIs, by enabling hands-free control and communication with spacecraft systems. This technology allows for a more natural and efficient interaction, by interpreting and responding to verbal commands. [25] Within the space sector, advanced speech recognition systems enhance user experience and safety, enabling astronauts and ground control to operate systems through voice command. [26]
- **Facial recognition technology** enhances security and personalization, by identifying and verifying individuals based on their facial features. This technology is used in space stations and mission control centers for personnel authentication, assuring that only authorized individuals can access certain areas, and for monitoring astronaut health, thereby improving security and operational efficiency. [27]
- **Touch displays and data gloves** represent significant advancements in tactile HMIs. Touch displays are widely used in spacecraft cockpits and mission control systems, providing intuitive and direct interaction with digital interfaces. [28] Data gloves, equipped with sensors, allow users to control systems through gestures, offering precise control in virtual environments and space operations.
- **Head-up display (HUD)** is revolutionizing the way astronauts interact with critical mission information. [29] Such a display projects essential data, such as speed, altitude and navigational cues, directly onto a visor or windshield, allowing an astronaut to keep their eyes on a task while at the same time accessing necessary information. [30] This technology enhances situational awareness and safety, by reducing the need for an astronaut to look down at instrumentation, thus enabling quicker decision-making and response times. HUDs are increasingly being integrated into modern spacecraft to improve operational efficiency and astronaut performance.

To further understand the technological advancements driving these innovations, the next section will dive into the patent data of these technologies, highlighting key developments and trends in the field. This analysis will provide insights into the proprietary innovations shaping the future of space transportation.

24 Burian, B. K., M. Ebnali, J. M. Robertson, D. Musson, C. N. Pozner, T. Doyle et al. (2023). Using extended reality (XR) for medical training and real-time clinical support during deep space missions. Applied Ergonomics, 106, 103902.
25 Salazar, G. (2022). Human systems integration approach in implementing voice-control of future spacecraft systems. In IEEE (Institute of Electrical and Electronics Engineers) Aerospace Conference, March 2022.
26 NASA (2022). Enabling a voice management system for space applications. National Aeronautics and Space Administration. Available at: https://ntrs.nasa.gov/api/citations/20210022373/downloads/Enabling%20a%20Voice%20Management%20System%20for%20Space%20Applications-ncr.pdf.
27 Korovin, I. S., A. B. Klimenko, I. A. Kalyaev and I. B. Safronenkova (2021). An experience of the cognitive map-based classifier usage in astronaut's emotional state monitoring. Acta Astronautica, 181, 537–543.
28 Beebe, N. K. (2022). Advanced onboard spacecraft guidance and navigation console. Doctoral dissertation.
29 Safi, M. and J. Chung (2023). Augmented reality uses and applications in aerospace and aviation. In Springer Handbook of Augmented Reality. Cham: Springer International Publishing, 473–494.
30 NASA (2021). Virtual and augmented reality technologies. National Aeronautics and Space Administration. Available at: www.nasa.gov/centers-and-facilities/armstrong/virtual-and-augmented-reality-techs.

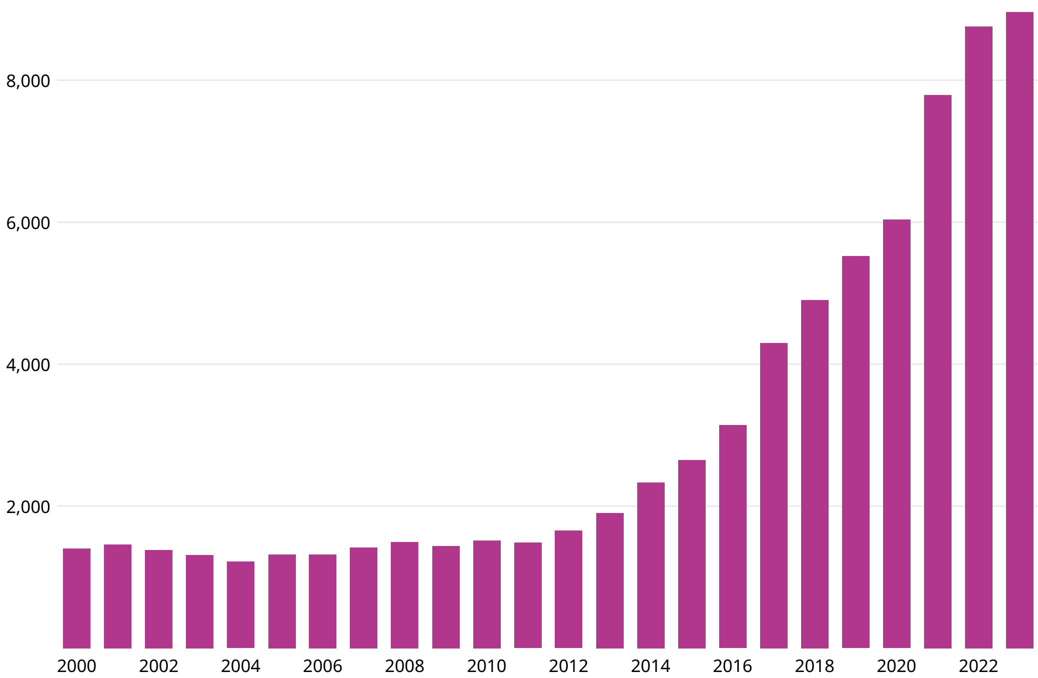
Global patent trends

Global patent development

After stagnating throughout the 2000s, global patenting activity in space technologies has accelerated significantly since 2011 (Figure D2). Between 2011 and 2023, the number of patent family publications increased six-fold, from around 1,400 to almost 9000 patent family publications in 2023. This corresponds to an compound annual growth rate (CAGR) of patent family publications of around 8% between 2000 and 2023, and around 15% between 2010 and 2023. In total, the patent search identified more than 67,000 patent families in the field of space transportation since 2000. Around 50,000 of these were considered active at the time of this analysis.

Since 2000, there have been more than 67,000 patent family publicationsin the field of space transportation

Figure D2 Development of global patent family publications, 2000–2023



Note: Patent family publications per earliest publication year.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

There are two main reasons for the acceleration of space exploration efforts since 2010. First, the emergence and rapid growth of private companies venturing into space in recent years has transformed space exploration, which was once dominated solely by government agencies.[1] This has brought in fresh ideas, spurred innovation and pushed the boundaries of what's possible in the exploration of space. These new entrants tend to fall into two categories: non-space companies, particularly large information and communication technology (ICT) companies such as Google or Facebook, keen to expand their activities and build on the synergies between ICT and space applications; and new private space companies, such as SpaceX, which use private and or public funding to initiate innovative business models and to address new space markets or existing space markets with disruptive solutions.[2] The emergence of these new private companies is leading the space sector toward a more business- and innovation-oriented scenario, often referred to as New Space.[3] This trend also enables public actors to consider more ambitious partnerships with industry, and to better share costs and risks with the private sector.

Second, a resurgence of the international space race, with new entrants such as China, India and Japan investing heavily in space technologies, has also been a driver of innovation activity. For example, Chinese startup LandSpace Technology plans to soon launch reusable rockets using a similar approach to SpaceX, while India aims to begin a series of flight tests for eventual crewed spaceflight in 2025.[4] Moreover, Japan succeeded in landing on the Moon in 2024, becoming only the fifth country to make it to the lunar surface.[5]

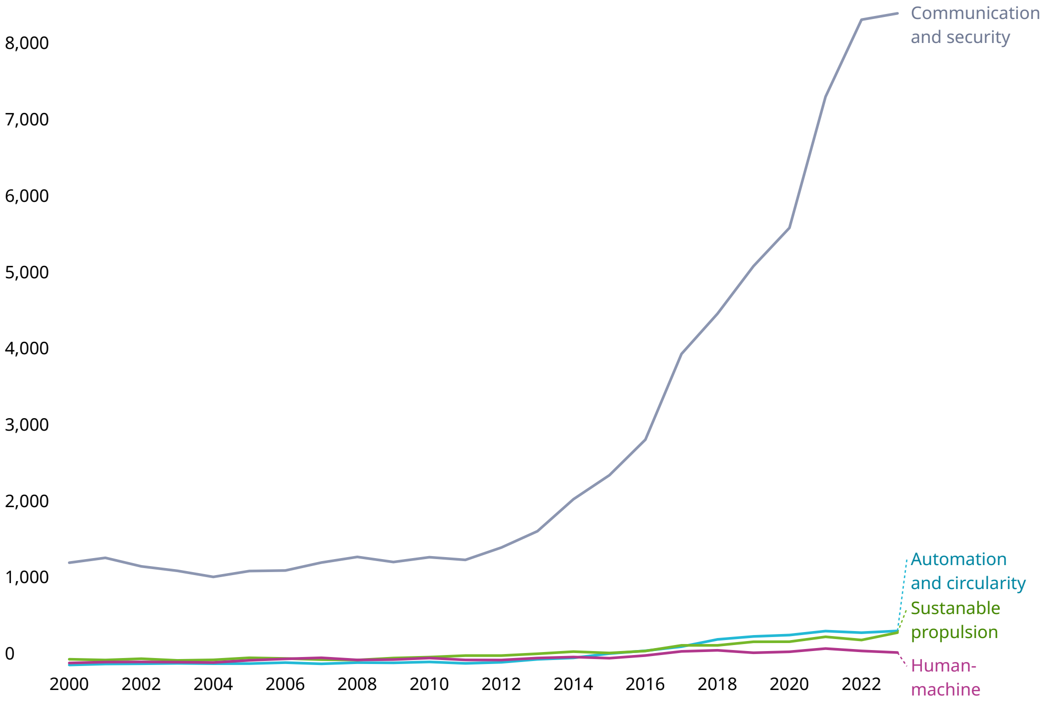
Overview of the four technology trends

To provide an overview of key technology trends, we analyzed and collected all patent family publications related to both space transport technologies (cosmonautics, satellites etc.) and one of the four key technology trends (Sustainable Propulsion/Efficient Aircraft Turbines, Automation and Circularity, Communication and Security, and Human–Machine Interface).

1 Medium (2023). The rise of private companies in space exploration: Revolutionizing the final frontier. Available at: https://medium.com/techcrate/the-rise-of-private-companies-in-space-exploration-revolutionizing-the-final-frontier-71d0a273b419.
2 ESPI (2017). The Rise of Private Actors in the Space Sector. European Space Policy Institute. Available at: www.espi.or.at/wp-content/uploads/2022/06/ESPI-report-The-rise-of-private-actors-Executive-Summary-1.pdf.
3 EPO (2021). Cosmonautics: The Development of Space-Related Technologies in Terms of Patent Activity. Munich: European Patent Office. Available at: www.econsight.ch/wp-content/uploads/2021/08/patent_insight_report-cosmonautics_en.pdf.
4 NikkeiAsia (2024). Space race to heat up in 2024 as Japan, China, India reach for the stars. Available at: https://asia.nikkei.com/Business/Aerospace-Defense-Industries/Space-race-to-heat-up-in-2024-as-Japan-China-India-reach-for-the-stars.
5 East Asia Forum (2024). Asia's ascendance in the new international space order. Available at: https://eastasiaforum.org/2024/05/22/asias-ascendance-in-the-new-international-space-order.

The dominant research efforts in space transportation are focused on Communication and Security

Figure D3 Development of patent family publications in the four technology trends, 2000–2023



Note: Some patent families are classified in more than one technology trend, therefore the sum of the four technology trends is larger than the total amount of patent family publications.

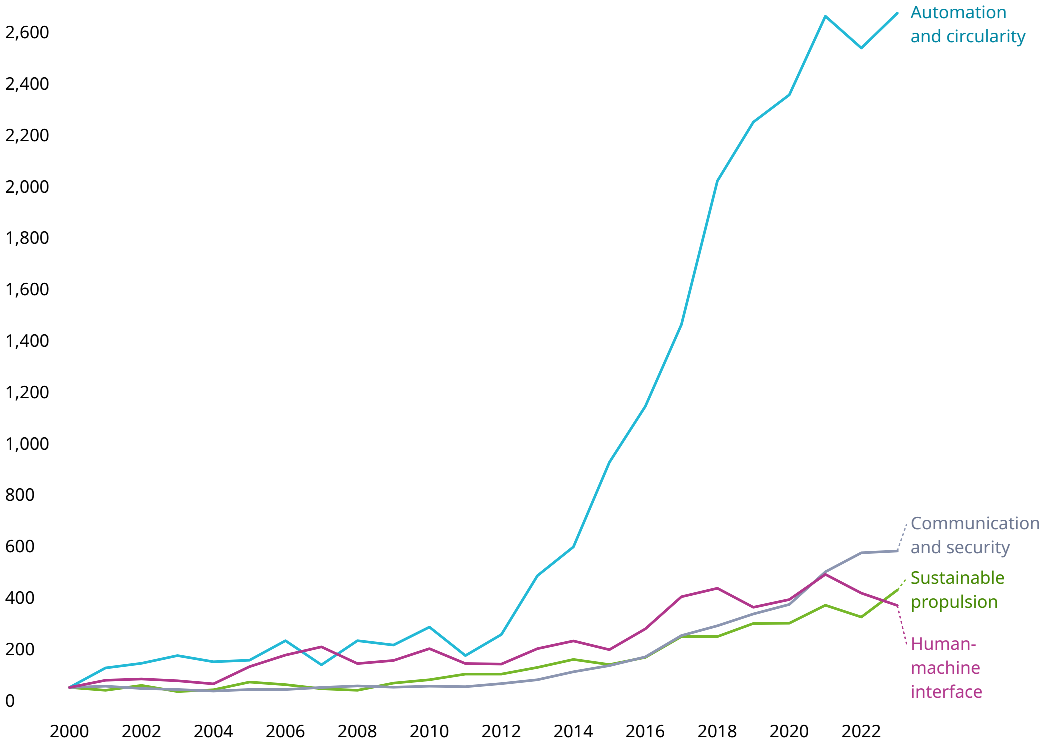
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

The vast majority of space research efforts are focused on Communication and Security technologies. Between 2000 and 2023, the number of published patent families in this area increased from around 1,350 to more than 8,500 (Figure D3). Patenting activity in Automation and Circularity technologies has increased from only 17 in 2000 to around 460 patent families published in 2023. A similar trend was observed in the field of Sustainable Propulsion. In Human–Machine Interface technologies, the number of patent families published worldwide increased from 43 in 2000 to 180 in 2023.

Patent growth has been highest in Automation and Circularity technologies, as shown in Figure D4, with a CAGR of 15% between 2000 and 2023 and a sharp acceleration since 2011. Patent growth in the other technology trends has been in the high single digits between 2000 and 2023.

When looking at the relative growth of patents among the four technology trends, the highest growth is in technologies related to Automation and Circularity

Figure D4 Indexed development of patent family publications in the four technology trends, 2000–2023



Note: Indexed development of patent family publications with patent family publications in 2000 = 100.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Patent coverage

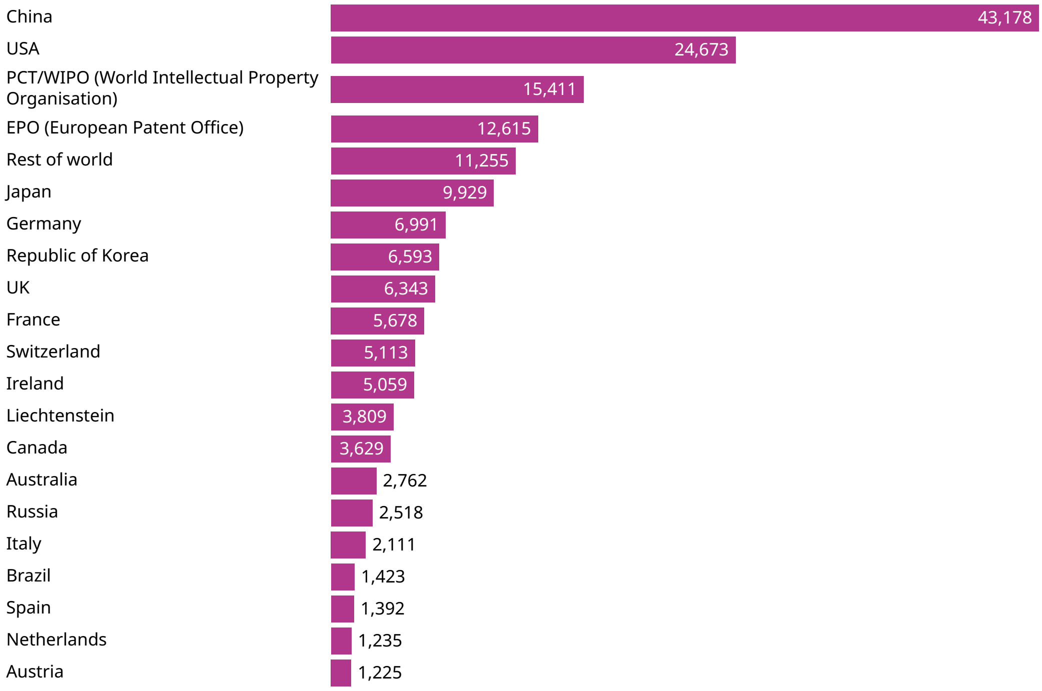
A look at the filing authorities of patent families in space transport technologies provides insights into global filing strategies.[6] Figure D5 shows China to be the top country in terms of patent filings. Between 2000 and 2023, more than 43,600 patent families in space transport technologies were filed in China seeking patent protection. The United States of America (US) has also attracted many patent filings since 2000 (24,673).

The third and fourth most important filing authorities are the Patent Cooperation Treaty (PCT) and European Patent Convention (EP). Since 2000, there have been more than 15,000 patent family publications under the PCT and almost 13,000 patent family publications via the EP route.

6 Members of patent families can be filed directly in one or more countries, via national patent offices, via the Patent Cooperation Treaty (PCT) route administered by WIPO or via the European Patent Convention (EP) route administered by the European Patent Office.

China leads in terms of the number of patents filed in space transportation technologies

Figure D5 Total patent publications by filing authority, 2000–2023



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Top inventor locations

Regional breakdown: space total

Based on the number of patent family publications, Asia is the most important research region for space exploration technologies. Between 2000 and 2023, there were 52,105 patent families published by inventors based in Asia (Figure D6). This represents 70% of all patent families identified. North America (17,342) and Europe (7,366) are other important research regions. The number of patent families from other regions (Africa, Latin America and the Caribbean (LAC) and Oceania) remains rather low.

Asia is the predominant location for space exploration technologies

Figure D6 Regional breakdown: total patent family publications, 2000–2023

Note: Some patent families are assigned to more than one region owing to the addresses of the inventors, which is why the sum of the shares is greater than 100%.

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Top inventor countries: space total

China and the United States are the leading research countries in space transportation technologies. Between 2000 and 2023, inventors from China published more than 38,000 patent families in these technologies, whereas inventors from the United States were responsible for the publication of almost 17,000 patent families (Figure D7).

Inventors from China are responsible for the highest number of patents related to space transportation technologies

Figure D7 Top inventor locations: total patent family publications, 2000–2023

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

China has become a leading nation in space technology research over the past few decades. The Government of China has consistently prioritized space exploration as a key aspect of its national development strategy. Central to these efforts is the China National Space Administration (CNSA) established in 1993, which oversees the nation's space missions and research initiatives. China's space program has made significant progress, including manned space flights, lunar exploration and the development of its own space station, Tiangong. These milestones are supported by a robust launch vehicle program, including the Long March rocket series.

Key players in China's space technology landscape extend beyond the CNSA to include aerospace companies and research institutions such as the China Aerospace Science and Technology Corporation (CASC), the China Academy of Space Technology (CAST) and the China Academy of Launch Vehicle Technology (CALT). The integration of academic research, state-owned enterprises and government policy has fostered a cohesive ecosystem that supports innovation. China has ambitious goals for the future in space such as building a permanent lunar research station.[1] The country also aims to develop more powerful and partly reusable rockets and explore deeper into the solar system, possibly including missions to Mars.[2]

The United States has been at the forefront of space technology research since the mid-20th century. The country has long been the most prominent actor in the global space sector with the highest annual public space budget.[3] This has been driven by a combination of government ambition, private sector innovation and extensive scientific collaboration. Since its creation in 1958, the National Aeronautics and Space Administration (NASA) has been the principal agency at the forefront of the nation's space exploration efforts. Its mission has led to achievements such as the Apollo Moon landings and the Space Shuttle program. In recent years, NASA's focus has expanded to include the Artemis program,[4] which aims to return humans to the Moon and

1 The Guardian (2014). The new 'space race': What are China's ambitions and why is the US so concerned? Available at: www.theguardian.com/world/article/2024/may/05/the-new-space-race-what-are-chinas-ambitions-and-why-is-the-us-so-concerned.
2 The Diplomat (2023). China's space program in 2023: Taking stock. Available at: https://thediplomat.com/2023/12/chinas-space-program-in-2023-taking-stock.
3 EPO (2021). Cosmonautics: The Development of Space-Related Technologies in Terms of Patent Activity. Munich: European Patent Office. Available at: www.econsight.ch/wp-content/uploads/2021/08/patent_insight_report-cosmonautics_en.pdf.
4 NASA. Artemis. National Aeronautics and Space Administration. Available at: www.nasa.gov/humans-in-space/artemis.

establish a sustainable presence there, and eventually to Mars. In addition, Mars rover missions, particularly the recent Perseverance rover, have advanced an understanding of Mars, the red planet.

The role of the private sector has become increasingly important in US space efforts, with companies such as SpaceX, Blue Origin and Boeing playing key roles. [5] SpaceX, founded by Elon Musk, has revolutionized space travel with its Falcon and Starship rockets, pioneering reusable rocket technology and significantly lowering the cost of access to space.

Japan has carved out a significant role in space technology. This is reflected in patent numbers, with Japan having published more than 6,500 patent family publications since 2000 (Figure D7). Japan's space technology ecosystem is bolstered by a combination of governmental agencies, academic institutions and private companies. The Japan Aerospace Exploration Agency (JAXA) established in 2003 is the primary body overseeing Japan's space exploration activities. Private companies like Mitsubishi Heavy Industries, which is responsible for the H-IIA and H-IIB launch vehicles, play a crucial role in launching satellites and other payloads into space. [6] Key developments in Japan's space program underscore its growing capabilities and ambitions. The Hayabusa missions demonstrated advanced technologies in space navigation, sample collection and re-entry. Another significant achievement is the Kibo module on the International Space Station (ISS), which is Japan's largest single contribution to the ISS and used for various scientific experiments in microgravity. [7]

The Republic of Korea is ranked fourth in terms of patent family publications, with around 4,500 publications between 2000 and 2023. The Korea Aerospace Research Institute (KARI), established in 1989 is the central agency driving the country's space ambitions. [8] In addition, the Korea Aerospace Administration (KASA) was established in 2024. Its goal is to oversee space policy and seek to foster space-related enterprises. The country has ambitious goals and has committed to spending 100 trillion won (USD 72.6 billion) on space exploration up until a planned Mars landing mission in 2045. [9]

France and Germany are the leading European locations in space technology research. Both countries have published more than 2,100 patent family publications since 2000 and deliver substantial financial and technological contributions to the European Space Agency (ESA), and also have their own national space programs. Both countries have a strong heritage in aerospace engineering and science, supported by extensive government funding and industrial capability. Germany has made a significant contribution, particularly in areas such as satellite development and space robotics. The German Aerospace Center (DLR) is the key player in Germany. France is a leading contributor to the Ariane launch vehicle program. CNES (Centre national d'études spatiales) is the top space research institution in France. CNES has developed a series of highly successful satellites, including the SPOT series for Earth observation and the HELIOS series for military reconnaissance. Key private players include major aerospace companies such as Airbus Defence and Space and Thales, which have significant operations in both Germany and France.

Other important countries for space research are the Russian Federation (1,762 patent family publications since 2000) and the United Kingdom (UK) (1,444). Canada (896) and India (514) rank ninth and 10th, respectively.

Development and patent growth since 2000

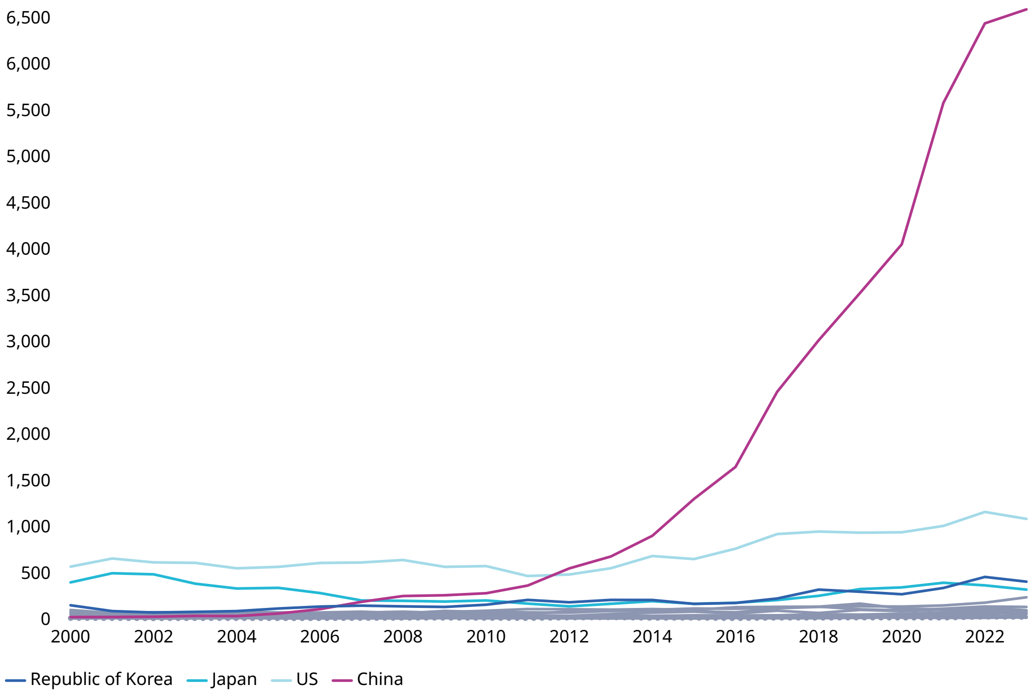
Figure D8 illustrates the impressive growth of Chinese research efforts in the field of space exploration over the last two decades. From a mere 15 patents in 2000, the number of patent family publications from China had multiplied to almost 6,600 in 2023. In the process, China overtook the United States in terms of annual patent publications as early as 2012 and has held

5 Harvard Business Review (2021). The commercial space age is here. Available at: https://hbr.org/2021/02/the-commercial-space-age-is-here.
6 Mitsubishi Heavy Industries. MHI Launch Services. Available at: www.mhi.com/products/space/launch_service.html.
7 NASA. Japanese experiment module Kibo. National Aeronautics and Space Administration. Available at: www.nasa.gov/international-space-station/japanese-experiment-module-kibo.
8 The Korea Times (2024). KARI plays pivotal role in Korea's space development. Available at: www.koreatimes.co.kr/www/tech/2024/07/129_366778.html.
9 Space.com (2024). South Korea creates new KASA space agency, sets sights on the moon and Mars. Available at: www.space.com/south-korea-space-agency-mars-landing-2045.

top spot ever since. In the United States, the number of patent family publications in space science has grown at a more modest rate, from 560 in 2000 to 1,076 in 2023. In contrast, patent family publications stagnated in Japan and even decreased in the Russia Federation between 2000 and 2023.

China overtook the United States in annual patent publications in 2012 and has remained in the top spot since then

Figure D8 Top 10 inventor locations: development of patent publications, 2000–2023

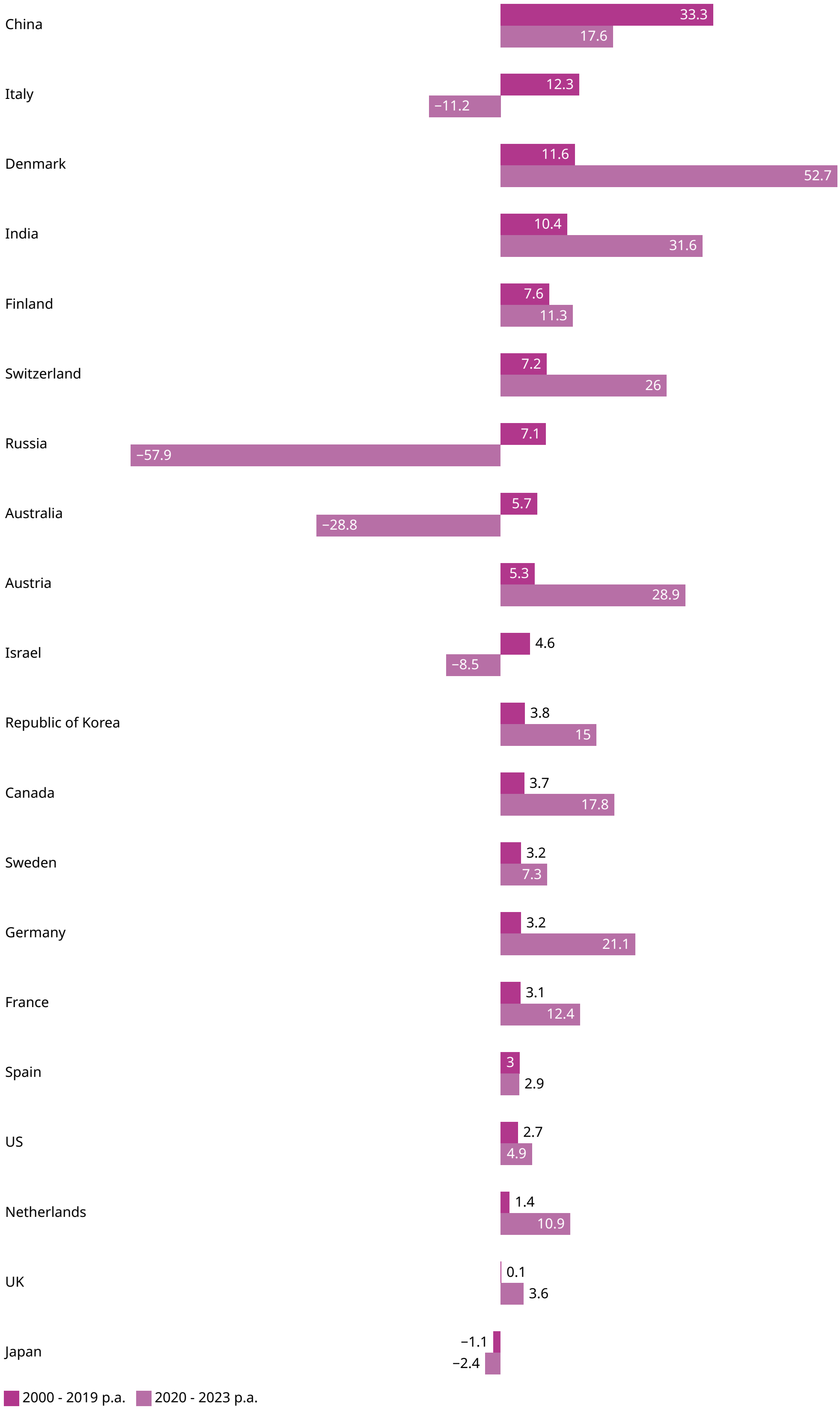


Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Regarding the growth rates of patent families, Asian countries China and India plus the European countries Denmark and Finland stand out, with very dynamic growth rates both between 2000 and 2019 and between 2020 and 2023 (Figure D9). In Italy, patenting activity grew at a dynamic rate between 2000 and 2019, but has been declining since then. The same is true for the Russian Federation, Australia and Israel.

Asian countries such as China and India, along with European nations like Denmark and Finland, stand out for their dynamic growth rates from 2000 to 2019 and between 2020 and 2023

Figure D9 Top inventor locations: compound annual growth rate of patent family publications, 2000–2019 and 2020–2023



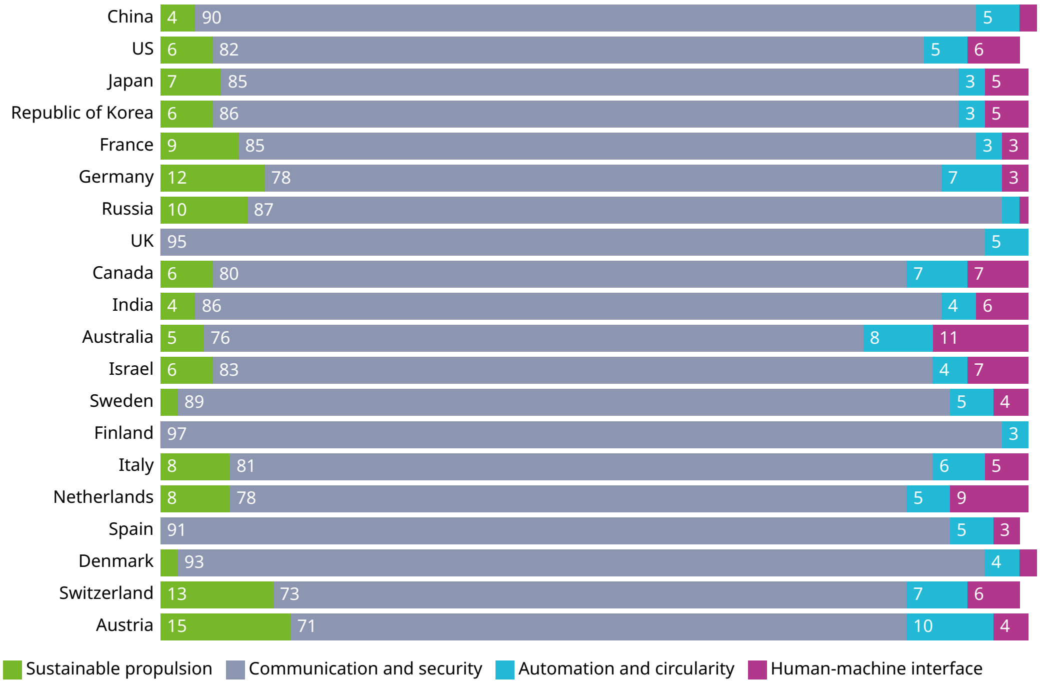
Note: Only countries with at least 100 patent family publications between 2000 and 2023 were considered.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Research priorities: countries

A closer look at research priorities at country level shows that the technology trend Communication and Security is the dominant research focus for all top researching countries (Figure D10 and Table D1). However, there are some differences in respect to the other three technology trends. For example, an above-average focus on the development of Sustainable Propulsion for spacecraft is observed in Switzerland, Austria, Germany and the Russian Federation. Austria also has above average patenting activity in Automation and Circularity. Australia and the Kingdom of the Netherlands have the largest share of patent families published in Human–Machine Interface technologies compared to all patents.

Communication and Security technologies are the dominant focus across all leading research nations

Figure D10 Top 20 countries: research priorities, by share



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

There are notable differences when it comes to the other three technology trends

Table D1 Top countries: research priorities

	Sustainable propulsion	Automation and circularity	Communication and security	Human-machine interface
China	1,468	2,019	36,631	700
US	1,265	1,037	16,134	1,280
Japan	532	233	6,195	355
Republic of Korea	306	160	4,404	265
France	210	73	2,016	66
Germany	276	167	1,873	80
Russia	188	39	1,576	16
UK	0	70	1,353	0
Canada	59	73	840	74
India	21	24	500	35
Australia	34	48	479	68
Israel	31	23	466	42
Sweden	8	22	371	15
Finland	0	9	326	0
Italy	27	20	282	18
Netherlands	21	15	217	26
Spain	0	12	202	7
Denmark	4	8	199	4
Switzerland	30	17	170	15
Austria	23	15	107	6

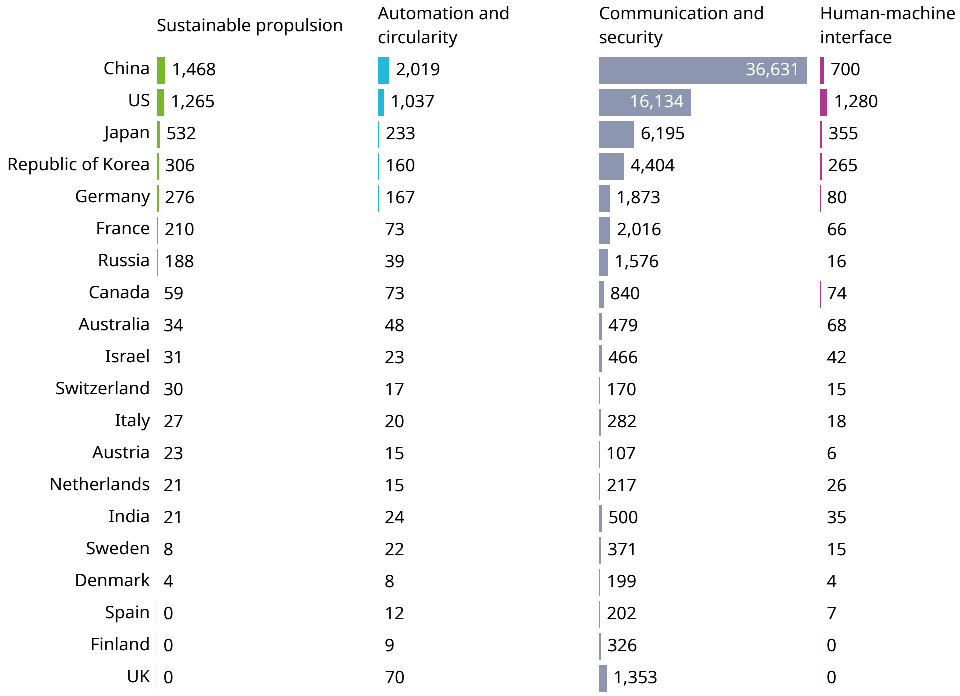
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Top inventor locations in the four technology trends

At the level of the four technology trends, China leads in Sustainable Propulsion, Communication and Security and Automation and Circularity technologies in terms of patent family publications (Figure D11). The United States ranks first in Human–Machine Interface technologies.

China leads in patent family publications for Sustainable Propulsion, Communication and Security, and Automation and Circularity technologies

Figure D11 Total patent family publications, 2000–2023



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Relative Specialization Index

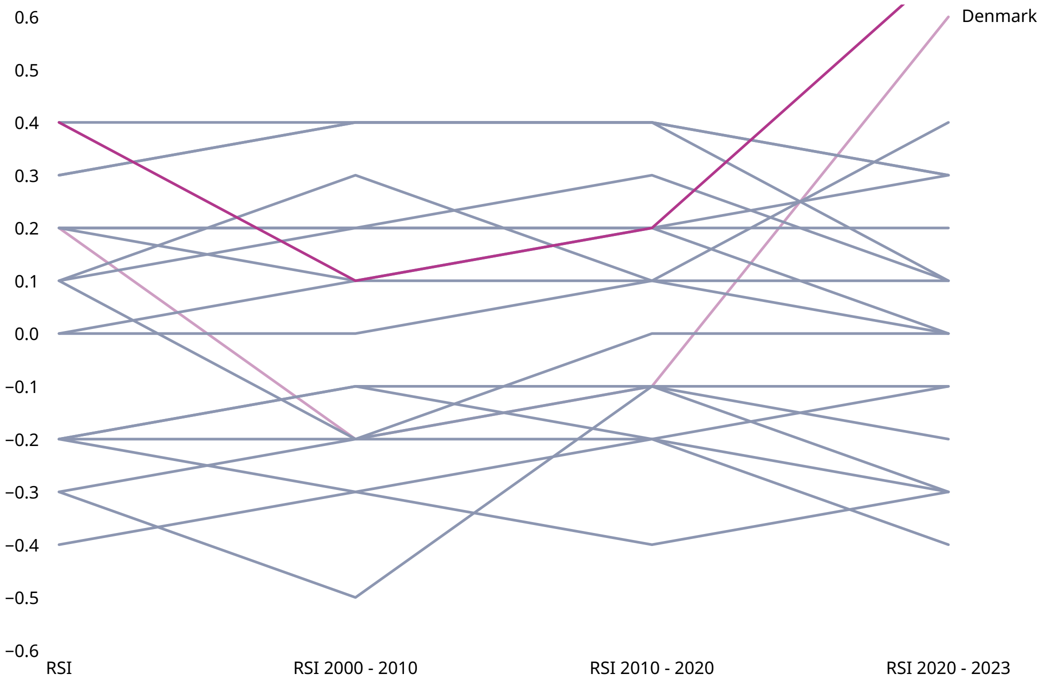
The Relative Specialization Index (RSI) is a measure that compares a country's (or company's) patenting activity in a specific research field with its overall patenting activity. It shows how specialized a country is in a particular field compared to its overall research profile. A positive RSI indicates that a country is more specialized in a particular field than the world average, whereas a negative RSI indicates that a country is less specialized in a particular field than the world average.

The RSI for space transportation technologies illustrates the extraordinary importance of space research in Finland and Denmark (Figure D12). The RSI in both countries has increased significantly since 2000.

At the other end of the ranking of the top 20 countries in space transport research are the Kingdom of the Netherlands and Japan, where a negative RSI value indicates a low degree of specialization.

Denmark and Finland are specializing more in space research

Figure D12 Top 20 countries: relative specialization, 2000–2023



Note: RSI is relative specialization index.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Top patent owners

Top patent owners: patent activity

The Chinese Academy of Sciences and the China Aerospace Science and Technology Corporation have published the most patent families in analyzed space technologies since 2000 (Figure D13). Boeing (United States), Mitsubishi Electric (Japan) and China Electronics Technology Group (China) are the other top 5 patent owners. Airbus is the first European company in the ranking, in sixth place.

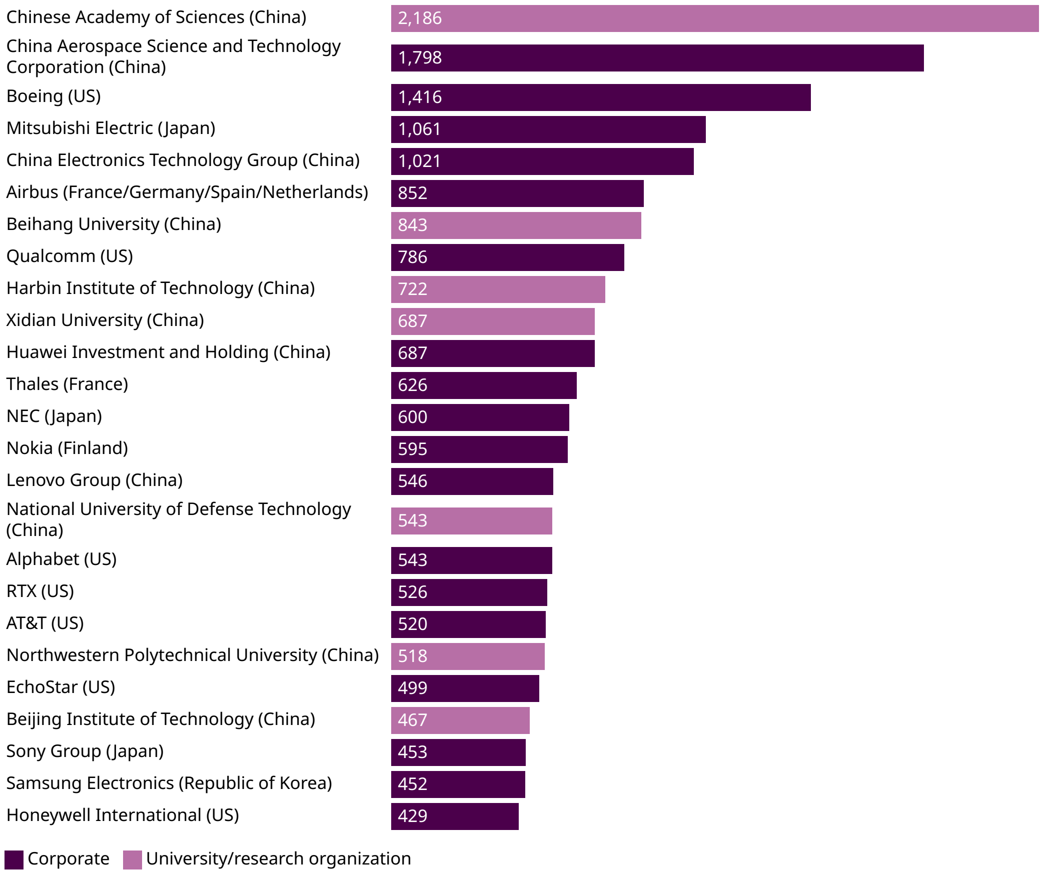
The National Space Science Center (NSSC) of the Chinese Academy of Sciences (CAS) is China's main hub for space science. It oversees the planning, development, management and operation of the country's space science satellite missions and plays a crucial role in China's Lunar and Deep Space Exploration Program.[1] The China Aerospace Science and Technology Corporation (CASC) is a state-owned enterprise and a major research player for space exploration and technology in China. Multiple entities involved in different aspects of space technology belong to CASC, including for example the China Academy of Space Technology (CAST).

Boeing plays a pivotal role in space research in the United States, contributing significantly to NASA's space missions. Boeing designs, manufactures and operates advanced spacecraft, satellites and launch systems. Notable contributions include the development of the Space Launch System (SLS)[2] for NASA's Artemis program and the CST-100 Starliner spacecraft,[3] designed to transport crew to the International Space Station and other low-Earth orbit destinations.

1 NSSC. Introduction. National Space Science Center (NSSC) of Chinese Academy of Sciences (CAS). Available at: http://english.nssc.cas.cn/about/introduction.
2 Boeing. Space launch system: Rocket to the Moon, Mars and beyond. Available at: www.boeing.com/space/space-launch-system#rocket.
3 Boeing. CST-100 Starliner: A 21st century space capsule. Available at: www.boeing.com/space/starliner#overview.

Although corporations dominate the list of top patent holders, there are several universities/research organizations too, with the top spot held by a research organization

Figure D13 Top patent owners, 2000–2023



Source: WIPO, based in patent data from EconSight/IFI Claims, October 2024.

Does SpaceX have patents?

SpaceX has become a major innovator in space research through its innovative approach to spacecraft and rocket design. The company has achieved numerous milestones, including the development of the Falcon rockets, which have lowered the cost of access to space. SpaceX's Dragon spacecraft was the first commercial vehicle to deliver cargo to the International Space Station (ISS) and SpaceX now carries astronauts to the ISS as part of NASA's Commercial Crew Program.[4] With ambitious goals such as the Starship project[5] to colonize Mars, SpaceX continues to push the boundaries of space technology and exploration.

SpaceX has filed only a low double-digit number of patents for its research activities in the space technologies analyzed, which mainly cover satellite technologies but not rocket technology. The company prefers to go the "trade secret" route rather than patenting its technology. Company founder Elon Musk argued in 2012 that SpaceX does not want to allow competitors to use published SpaceX patents "as a recipe book."[6] However, there are risks to keeping trade secrets, as they can be leaked or stolen. In addition, trade secret protection does not protect against independent discovery or reverse engineering.[7]

4 SpaceX. Space station: Transporting humans to the orbiting laboratory in the sky. Available at: www.spacex.com/humanspaceflight/iss.
5 SpaceX. Starship: Service to Earth orbit, Moon, Mars and beyond. Available at: www.spacex.com/vehicles/starship.
6 Wired (2012). Elon Musk's mission to Mars. Available at: www.wired.com/2012/10/ff-elon-musk-qa.
7 Patent Forecast (2021). Where are SpaceX's patents? Its trade secrets strategy is fraught with peril. Available at: www.patentforecast.com/2021/05/27/where-are-spacexs-patents-its-trade-secrets-strategy-is-fraught-with-peril.

Top patent owners: patent growth

Patenting activity in the analyzed space transport technologies has grown dynamically over the last decades (Figures D14–D18). Many top patent owners have expanded their patent portfolios over the entire period analyzed from 2000 to 2023. This is especially true for communication companies like Qualcomm and Nokia which have increased their patenting activity significantly (Figure D16) since 2000. has context menuhas context menu

Companies in the Communication and Security area show the highest growth

Table D2 Compounded annual growth rate (CAGR) for top patent owners for different time periods

Patent owner	Growth 2020–2023 p.a.(%)	Growth 2018–2023 p.a. (%)	Growth 2013–2023 p.a. (%)	Growth 2000–2023 p.a. (%)
NEC (Japan)	99	49	27	3
Qualcomm (US)	97	35	31	6
Samsung Electronics (Republic of Korea)	95	79	57	12
Nokia (Finland)	65	118	35	6
Lenovo Group (China)	61	54	70	18
Huawei Investment and Holding (China)	54	99	62	N/A
Northwestern Polytechnical University (China)	41	16	28	N/A
China Electronics Technology Group (China)	39	26	35	N/A
Harbin Institute of Technology (China)	28	17	17	N/A
Beihang University (China)	25	–2	13	N/A
Beijing Institute of Technology (China)	19	26	20	N/A
AT&T (US)	19	6	18	7
National University of Defense Technology (China)	15	14	18	N/A
China Aerospace Science and Technology Corporation (China)	13	10	12	N/A
Xidian University (China)	12	4	39	N/A
Alphabet (US)	11	3	5	5
EchoStar (US)	9	3	14	8
Airbus (France/Germany/Spain/Netherlands)	8	–5	–1	1
Mitsubishi Electric (Japan)	3	0	–0	–3
Chinese Academy of Sciences (China)	–1	16	23	23
Sony Group (Japan)	–1	39	38	3
Honeywell International (US)	–4	–17	3	3
RTX (US)	–5	6	2	6
Thales (France)	–17	–10	0	6
Boeing (US)	–32	–19	–11	3

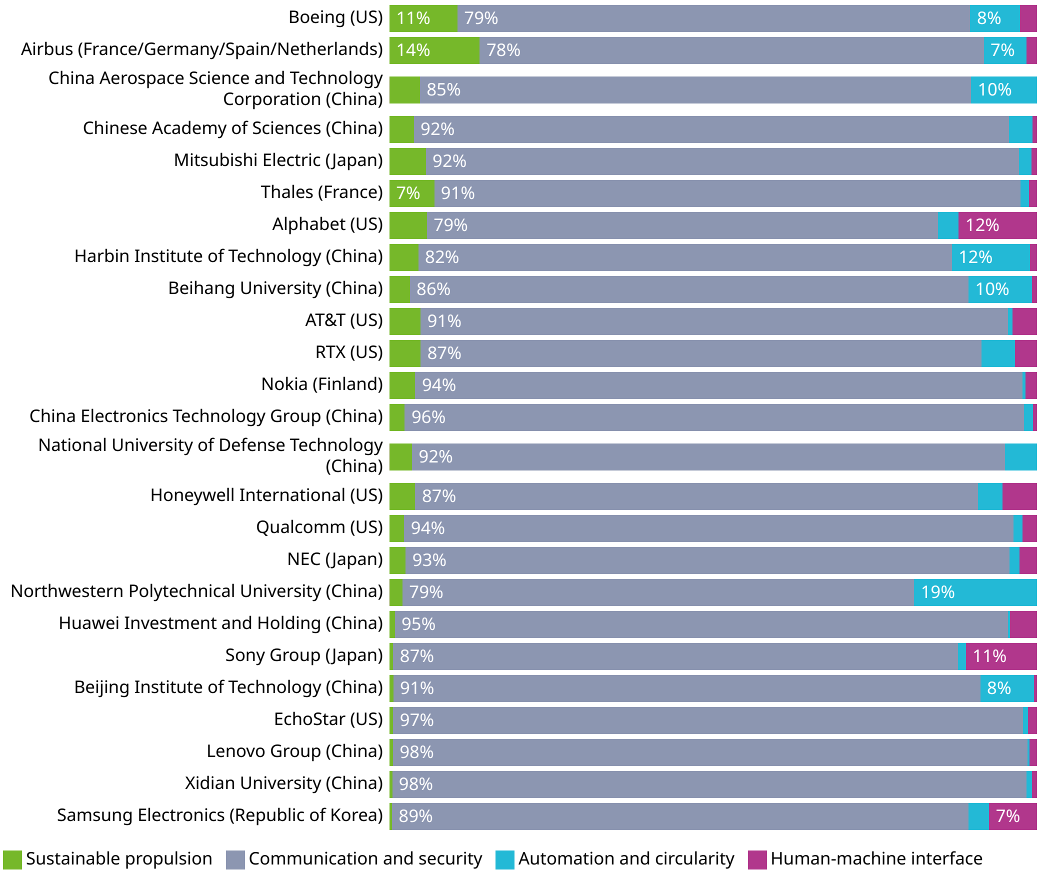
Notes: N/A indicates owner had no patents in 2000. Names in bold indicate universities/research organizations.
Source: WIPO, based in patent data from EconSight/IFI Claims, October 2024.

Top patent owners: research priorities

Research priorities show that all top patent applicants clearly focus their research efforts on the development of Communication and Security technologies (Figure D14).

All leading patent owners clearly concentrate research efforts on advancing Communication and Security technologies

Figure D14 Top 25 patent owners: research priorities



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

In absolute terms, the Chinese Academy of Sciences has developed and published the largest number of patent families (2,120) in Communication and Security technologies (Figure D15).

However, there are a number of companies with significant research activities in the other three technology trends analyzed. For example, Boeing and Airbus are very active in the development of Sustainable Propulsion systems and have published the largest number of patent families in this technology trend since 2000 (Boeing, 173; Airbus, 133).

In respect to Automation and Circularity technologies, the China Aerospace Science and Technology Corporation (194), Boeing (126) and the Northwestern Polytechnical University of China (112) published the highest number of patent families between 2000 and 2023.

Human-Machine Interface in space transport applications is a particularly important research field for Alphabet (83 patent family publications) and Sony (56).

In absolute terms, the Chinese Academy of Sciences has developed and published the largest number of patent families in Communication and Security technologies

Figure D15 Top 25 patent owners: patent family publications, 2000–2023

	Sustainable propulsion	Communication and security	Automation and circularity	Human-machine interface
Boeing (US)	173	1,304	126	43
Airbus (France/Germany/Spain/Netherlands)	133	742	63	15
China Aerospace Science and Technology Corporation (China)	90	1,624	194	0
Chinese Academy of Sciences (China)	87	2,120	83	16
Mitsubishi Electric (Japan)	64	1,043	22	9
Thales (France)	47	616	9	8
Alphabet (US)	40	543	22	83
Harbin Institute of Technology (China)	35	646	95	8
Beihang University (China)	29	794	90	7
AT&T (US)	27	509	4	21
RTX (US)	27	486	29	19
Nokia (Finland)	25	588	3	11
China Electronics Technology Group (China)	25	1,010	15	6
National University of Defense Technology (China)	20	525	28	0
Honeywell International (US)	19	414	18	25
Qualcomm (US)	19	781	12	18
NEC (Japan)	16	593	10	17
Northwestern Polytechnical University (China)	12	467	112	0
Huawei Investment and Holding (China)	6	686	2	30
Sony Group (Japan)	3	446	6	56
Beijing Institute of Technology (China)	3	447	41	2
EchoStar (US)	3	499	4	7
Lenovo Group (China)	3	545	2	6
Xidian University (China)	3	686	6	5
Samsung Electronics (Republic of Korea)	2	448	16	37

Note: Names in bold indicate universities/research organizations.

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Patenting activity in the four technology trends

Sustainable Propulsion

A space propulsion system is the primary mobility system for a spacecraft, providing thrust for orbital acquisition, alteration, maintenance, attitude control, station keeping, attitude control, close-in operations, collision avoidance, decommissioning and deep-space maneuvering. [1] In addition to chemical and electric propulsion systems, advanced technologies such as air-breathing, hybrid, nuclear, tethered and solar sail propulsion are being researched. There is a particular focus on the development of more Sustainable Propulsion systems to reduce the environmental impact and resource consumption of space missions. Such systems aim to use more efficient energy sources and minimize harmful emissions. Sustainable Propulsion technologies, such as solar sails and electric propulsion systems powered by renewable energy, are gaining attention for their potential to provide long-term solutions for space travel. However, such systems often face limitations in terms of thrust and scalability, which can limit their applicability to certain types of mission.

In this report, the Sustainable Propulsion technology trend consists of the following four subcategories: batteries, electric propulsion, hydrogen/fuel cells, and sustainable carbon-based fuels.

The most important area in terms of patent family publications is electric propulsion (EP). The number of patent family publications in this area has increased from only 70 in 2000 to 293 in 2023 (Figure D16). EP systems are fuel efficient, using a fraction of the propellant required by chemical rockets for the same mission. [2] This results in lighter spacecraft, reducing launch costs and allowing more scientific instruments to be carried. In addition, EP systems can generate thrust for extended periods of time, allowing gradual acceleration and precise manoeuvring. However, challenges remain. Current EP systems rely mainly on solar panels for power, which limits their effectiveness in deep space, where sunlight is scarce. As a result, most spacecraft still rely on conventional chemical propulsion. Nonetheless, electric propulsion is widely used on geostationary Earth orbit commercial communications satellites.

The second most important research area is batteries, where patent family numbers have grown from 22 to 152 between 2000 and 2023. Advanced battery technologies play a role in storing and providing energy for electric propulsion systems. However, a limitation is the low energy density of current generation batteries. Still, there is potential for specific applications such as using batteries for short bursts for maneuvering in hybrid systems or for attitude control in small satellites with solar charging. [3] Future advancements in solid-state battery technology could unlock more possibilities for batteries in space.

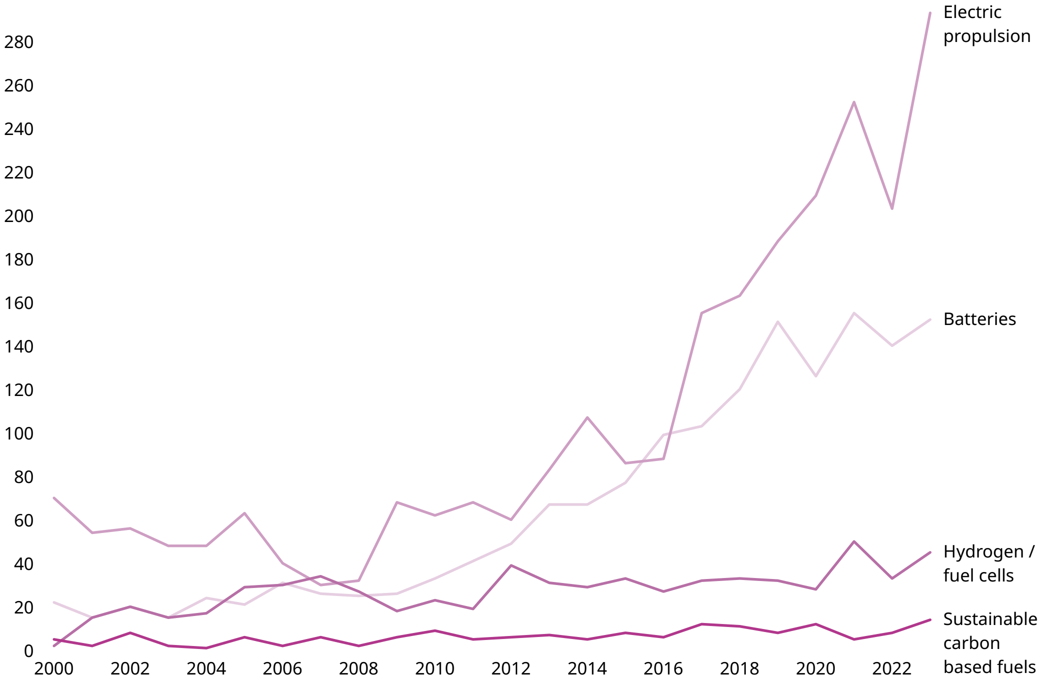
Patent family publications for the use of hydrogen/fuel cells in space applications have increased from 2 in 2000 to 45 in 2023. Fuel cells have already been used for the Apollo missions to provide

1 EPO (2021). Cosmonautics: The Development of Space-Related Technologies in Terms of Patent Activity. Munich: European Patent Office. Available at: www.econsight.ch/wp-content/uploads/2021/08/patent_insight_report-cosmonautics_en.pdf.
2 NASA (2020). The propulsion we're supplying, it's electrifying. National Aeronautics and Space Administration. Available at: www.nasa.gov/humans-in-space/the-propulsion-were-supplying-its-electrifying.
3 ESA (2009). Batteries at the heart of ESA space missions. European Space Agency. Available at: www.esa.int/Enabling_Support/Space_Engineering_Technology/Batteries_at_the_heart_of_ESA_space_missions.

both electricity and water for astronauts.[4] They continue to be a reliable and clean source of onboard power, especially on the International Space Station. However, the widespread use of hydrogen fuel cells in deep space exploration will depend on advances in storage technology. Solid-state hydrogen storage or techniques for extracting hydrogen from water ice on celestial bodies (i.e., in situ resource utilization) could be potential solutions. If these challenges can be overcome, the combination of fuel cells and hydrogen offers a promising way of powering future deep space missions. Their clean-burning nature, high energy density and potential for refueling on celestial bodies make them an attractive option.

The most important area in terms of patent family publications is electric propulsion

Figure D16 Sustainable Propulsion: development of global patent family publications, 2000–2023, earliest publication year



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

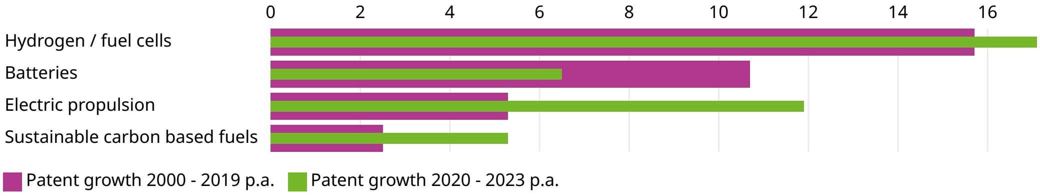
Patenting activity in the area of sustainable carbon-based fuels for space applications has remained limited over the last years. Still, sustainable fuels have a lot of potential, given the growing awareness of the environmental impact of traditional rocket propellants.[5] Sustainable fuels offer a cleaner alternative, reducing greenhouse gas emissions and contributing to a more sustainable space industry. However, balancing sustainability with performance is an ongoing challenge, since some sustainable fuels might not offer the same level of thrust or energy density as a traditional propellant. Moreover, the limited availability of sustainable fuels is a big challenge.

Innovation activity was very dynamic in all four technology trends in space transportation, looking at the CAGR over different time periods (Figures D17–D19). It is notable that patenting activity in the field of electric propulsion has accelerated significantly since 2020 (Figure D17).

4 Horizon Educational Group. Fuel cells: Powering spaceflight since 1965. Available at: www.horizoneducational.com/fuel-cells-powering-spaceflight-since-1965/t1442?currency=usd.
5 Fortune (2022). Space travel is heating up – and so are rocket fuel emissions: These companies are developing cleaner alternatives to protect earth first. Available at: https://fortune.com/2022/12/05/space-travel-is-heating-up-and-so-are-rocket-fuel-emissions-these-companies-are-developing-cleaner-alternatives-to-protect-earth-first.

Patenting activity in the field of electric propulsion has accelerated significantly since 2020

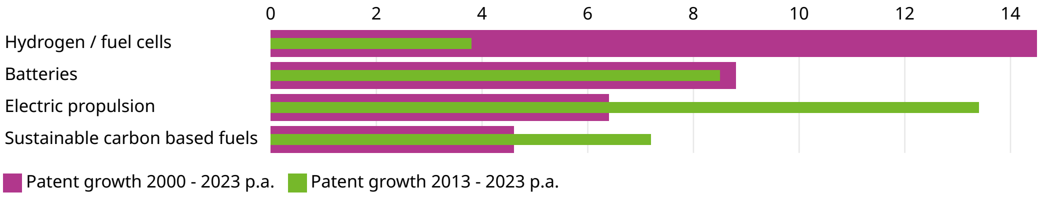
D17 Sustainable Propulsion: growth 2000–2019 and 2020–2023



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Innovation activity has been very dynamic in all four technology trends in space transportation, looking at the CAGR over different time periods

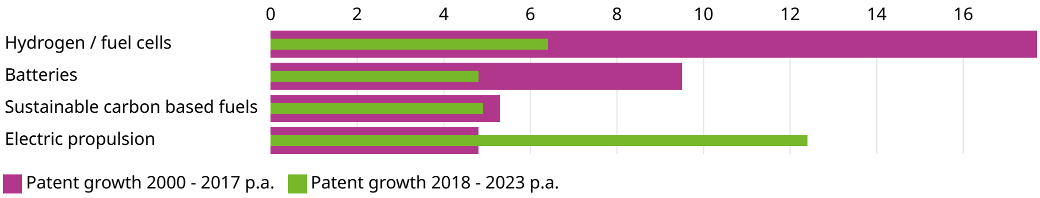
D18 Sustainable Propulsion: growth 2000–2023 and 2013–2023



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Patenting activity has been very dynamic in all four technology trends in space transportation

Figure D19 Sustainable Propulsion: growth 2000–2017 and 2018–2023



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Growth has been highest in electric propulsion and hydrogen/fuel cells

Table D3 Compound annual growth rate (CAGR) of sustainable propulsion technologies for different time periods

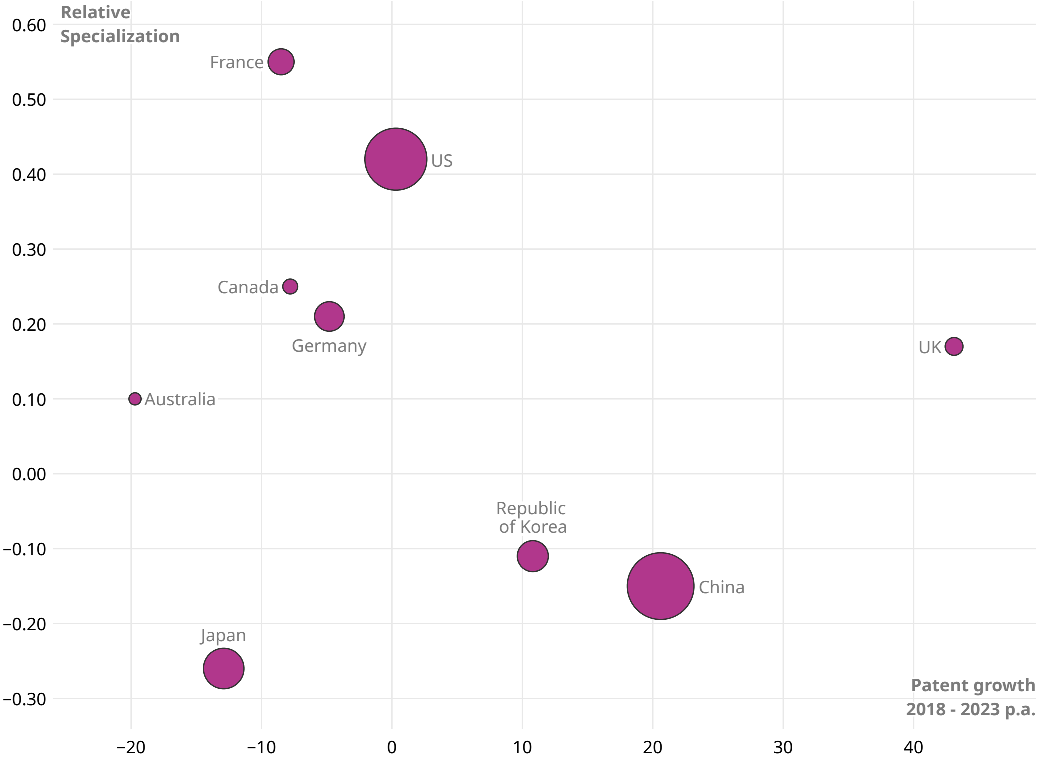
	Growth 2020–2023 p.a. (%)	Growth 2018–2023 p.a. (%)	Growth 2013–2023 p.a. (%)	Growth 2000–2023 p.a. (%)
Sustainable carbon based fuels	5	5	7	5
Batteries	7	5	9	9
Hydrogen / fuel cells	17	6	4	15
Electric propulsion	12	12	13	6

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Figure D20 shows that inventors from China and the United States are responsible for most patent family publications. In terms of patent growth in recent years, the United Kingdom stands out, with a CAGR of patent family publications of 43% since 2018. China and the Republic of Korea have also achieved very dynamic growth rates in the recent past. In terms of RSI, however, France and the United States have the highest values, indicating an above average degree of specialization.

The United Kingdom stands out with a compound annual growth rate (CAGR) of 43% in patent family publications since 2018

Figure D20 Sustainable Propulsion: country comparison, RSI (2000–2023) and growth rates (2018–2023)



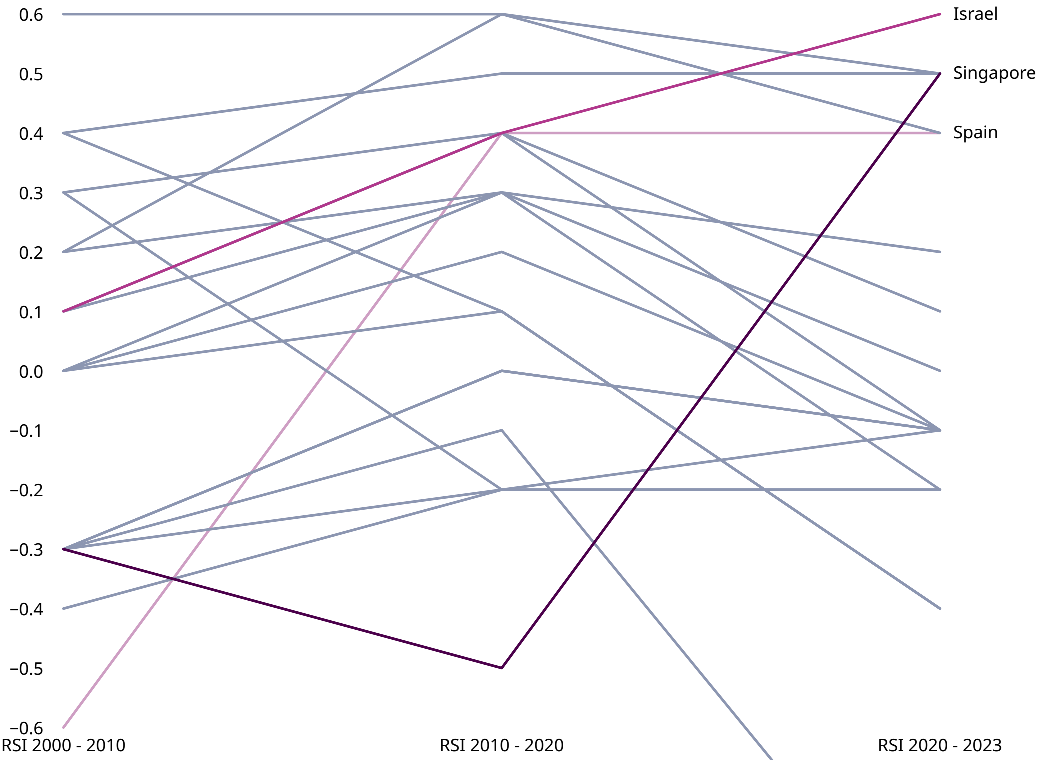
Notes: The size of the bubbles reflects the number of patent family publications at the country level in the field of Sustainable Propulsion. The CAGRare for 2018–2023, and the Relative Specialization Index (RSI) for the whole period analyzed, 2000–2023. The Russia Federation is among the top 10 inventor countries, but had a negative patent family growth rate of –100% between 2018 and 2023. For better readability, the Russian Federation is therefore not shown in the graph.

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

A closer look at RSI values over the different time periods for a broader group of countries shows that Israel has significantly increased its RSI in Sustainable Propulsion technologies for space applications over the last two decades (Figure D21). As a result, Israel has overtaken France at the top of the RSI ranking in the latest period 2020 to 2023. Other highly specialized countries include Singapore, the United States and Spain.

Israel has significantly increased its Relative Specialization Index (RSI) in Sustainable Propulsion technologies for space applications over the last two decades

Figure D21 Sustainable Propulsion: top 20 countries' 2000–2023 relative specialization



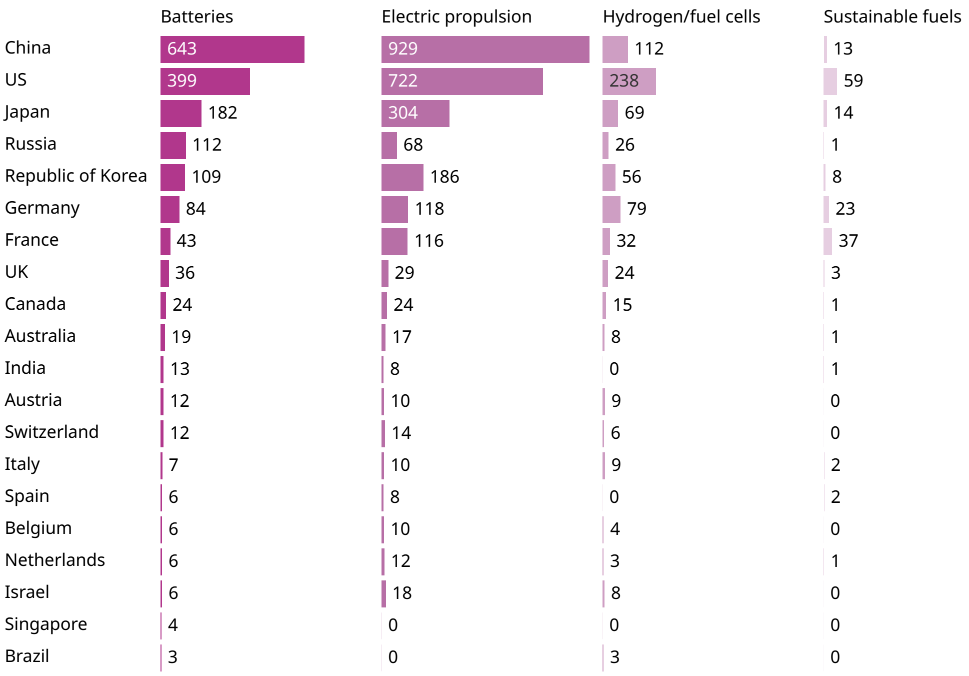
Note: RSI is relative specialization index.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

An analysis of the top research countries in the different Sustainable Propulsion subgroups reveals the following key findings (Figure D22):

- China is the technology leader in batteries, with 643 patent families published between 2000 and 2023. The United States and Japan follow in second and third place.
- China also leads in electric propulsion research, but the United States is not far behind in terms of number of patent families published.
- The United States leads in hydrogen/fuel cell research for space applications. China ranks second and Germany third.
- The United States also leads in the research and development of sustainable fuels. France ranks second.

Chinese inventors lead in batteries and electric propulsion while US inventors lead in hydrogen/fuel cells and sustainable fuels

Figure D22 Top 20 inventor locations for Sustainable Propulsion subgroups, 2000–2023



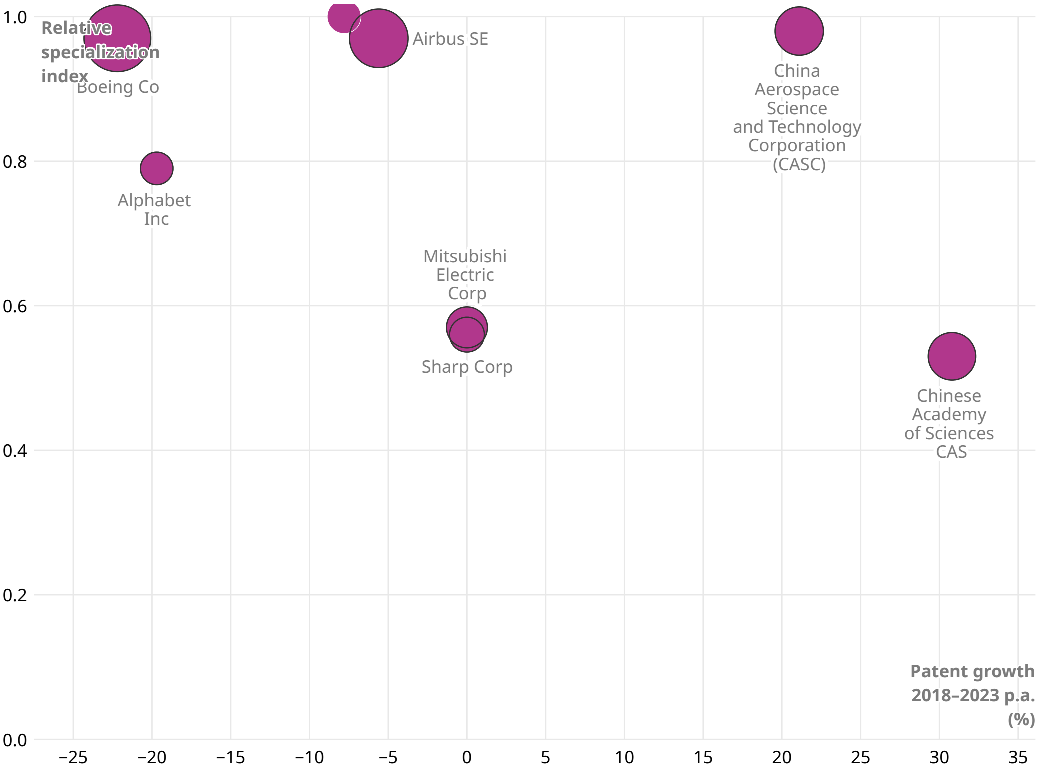
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Boeing and Airbus are the leading research companies in Sustainable Propulsion for space applications in terms of patent family publications, followed by the China Aerospace Science and Technology Corporation and the Chinese Academy of Sciences (Figure D23).

While the China Aerospace Science and Technology Corporation and the Chinese Academy of Sciences have greatly expanded their patent portfolios in Sustainable Propulsion for space applications over the last five years, the number of patent family publications by Airbus has stagnated and Boeing, Alphabet, Lockheed Martin and Thales have significantly reduced their patenting activity.

Boeing and Airbus are the leading research companies in Sustainable Propulsion for space applications in terms of patent family publications, followed by the China Aerospace Science and Technology Corporation and the Chinese Academy of Sciences

Figure D23 Sustainable Propulsion: comparison of top patent owners, RSI (2000–2023) and growth rates (2018–2023)



Notes: Lockheed Martin and Thales are among the top 10 patent owners but had a negative patent family growth rate of –100% between 2018 and 2023. For better readability, they are not shown in the graph. RSI is relative specialization index.

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

The top research players in the foursubgroups are as follows (Figure D24):

- Boeing, Airbus and China Aerospace Science and Technology Corporation are research leaders in batteries for space applications.
- Ariane Group, Boeing and Air Liquide have developed the most patent families for sustainable fuels.
- Boeing also leads in electric propulsion research.
- Airbus is the leader in research activities on hydrogen/fuel cell use in space.

Boeing, Airbus, and the China Aerospace Science and Technology Corporation are research leaders in batteries for space applications

Figure D24 Top 5 patent owners in the subgroups of Sustainable Propulsion, 2000–2023

Subgroup	Company	Patent family publications
Batteries	Contemporary Amperex Technology Co Ltd	24
Batteries	Alphabet Inc	25
Batteries	China Aerospace Science and Technology Corporation (CASC)	36
Batteries	Airbus SE	38
Batteries	Boeing Co	40
Electric propulsion	Sharp Corp	44
Electric propulsion	Mitsubishi Electric Corp	57
Electric propulsion	Chinese Academy of Sciences CAS	60
Electric propulsion	Airbus SE	68
Electric propulsion	Boeing Co	105
Hydrogen/fuel cells	Aerovironment Inc	7
Hydrogen/fuel cells	Alphabet Inc	7
Hydrogen/fuel cells	Chinese Academy of Sciences CAS	11
Hydrogen/fuel cells	Boeing Co	18
Hydrogen/fuel cells	Airbus SE	33
Sustainable fuels	OHB SE	8
Sustainable fuels	Airbus SE	13
Sustainable fuels	Air Liquide SA	14
Sustainable fuels	Boeing Co	16
Sustainable fuels	ArianeGroup SAS	18

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Automation and Circularity

Automation and Circularity technologies in the space transport field include the areas smart production (including automation and robotics), efficient material use and recycling. Robotics technologies have a history closely associated with human space exploration, enabling the performance of tasks in remote and extreme environments such as celestial body exploration. Planetary and orbital robotics are the most prominent applications and concepts of these systems.[6] For example, the use of automation and robotics technologies is essential for mitigating space debris in orbital systems.

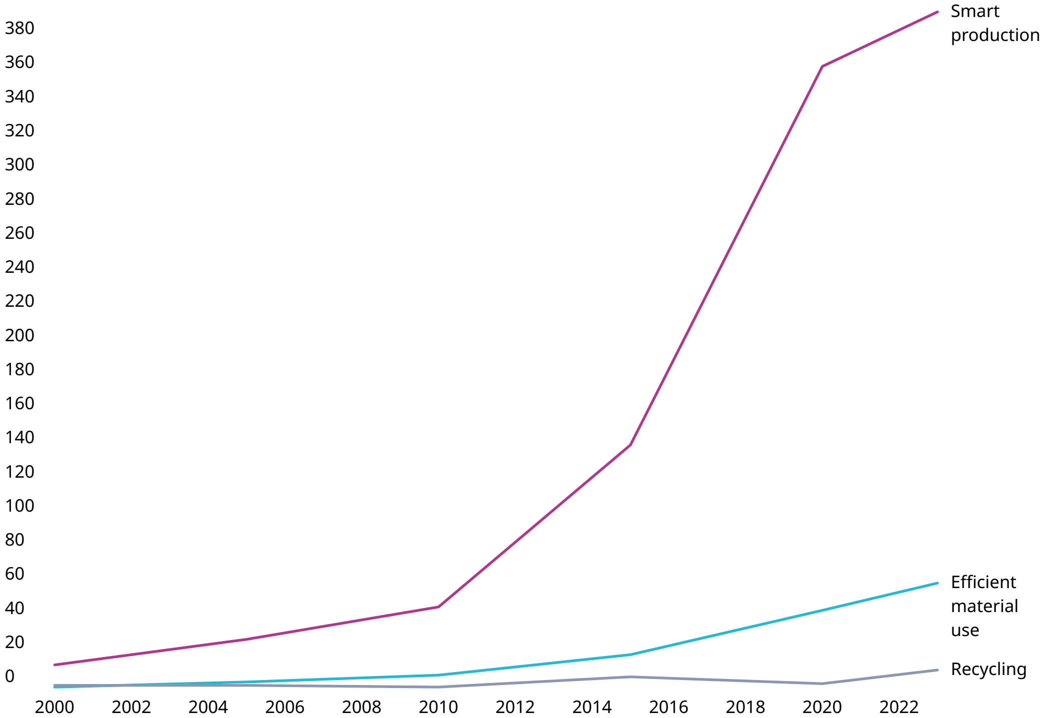
In terms of patent families published, the research field of smart production, including robotics and automation technologies, is by far the most important, with 397 patent family publications in 2023 alone (Figure D25). Patent family publications in the field of efficient use of materials have also increased steadily over the last two decades, but the level of patenting

6 EPO (2021). Cosmonautics: The Development of Space-Related Technologies in Terms of Patent Activity. Munich: European Patent Office. Available at: www.econsight.ch/wp-content/uploads/2021/08/patent_insight_report-cosmonautics_en.pdf.

activity remains lower, with 62 publications in 2023. Patenting activity in recycling related to space activities remains modest, with only 11 patent family publications in 2023. Nonetheless, recycling technologies are becoming increasingly important. By turning waste into reusable resources, such technologies address the challenges of limited space, high launch costs and environmental impact, helping to make space exploration more sustainable.

In terms of patent families published, smart production, including robotics and automation technologies, is by far the most important research field

Figure D25 Automation and Circularity: development of global patent family publications, 2000–2023

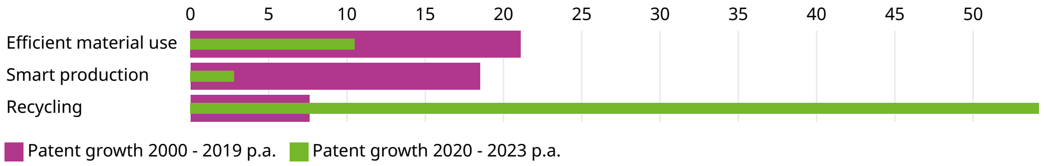


Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Innovation activity has been dynamic in all Automation and Circularity technologies over the period 2000 to 2023 (Figures D26–D28). However, in the most recent years since 2020, patent growth rates have slowed down noticeably in smart production technologies, while growth rates have been very high in recycling, albeit from a very low level (Figure D26).

Since 2020, patent growth rates in smart production technologies have slowed noticeably, whereas recycling technologies have seen very high growth rates, albeit from a low starting point

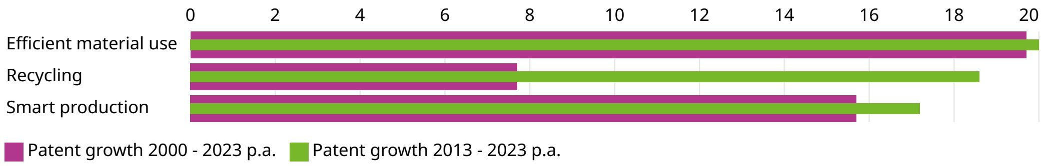
Figure D26 Automation and Circularity: growth of patent family publications, 2000–2019 and 2020–2023



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Innovation activity has been dynamic across all Automation and Circularity technologies from 2000 to 2023

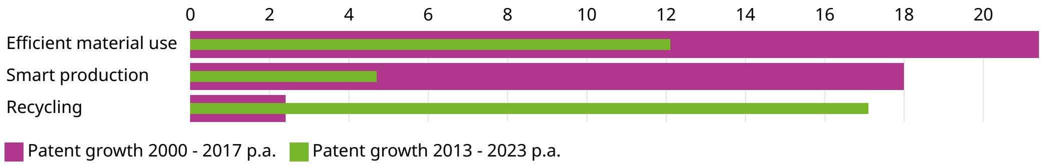
Figure D27 Automation and Circularity: growth of patent family publications, 2000–2023 and 2013–2023



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Patent growth in efficient material use has been exceptionally high across all analyzed time periods

Figure D28 Automation and Circularity: growth of patent family publications, 2000–2017 and 2013–2023



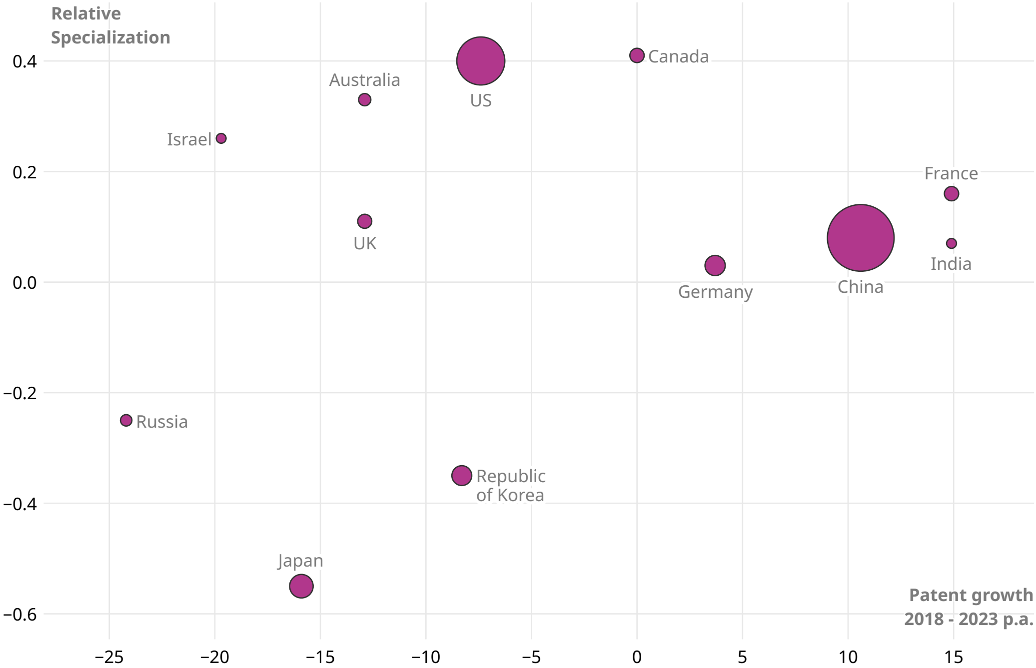
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Figure D29 shows that inventors from China are responsible for most patent family publications. In addition, the CAGR of patent family publications from China since 2018 has reached more than 10%. Only France and India have achieved even higher patent growth rates in recent years.

In terms of RSI, Canada, the United States and Australia have the highest values, indicating an above average degree of specialization.

Chinese inventors lead in patent family publications, with a CAGR exceeding 10% since 2018

Figure D29 Automation and Circularity: country comparison, RSI (2000–2023) and growth rates (2018–2023)



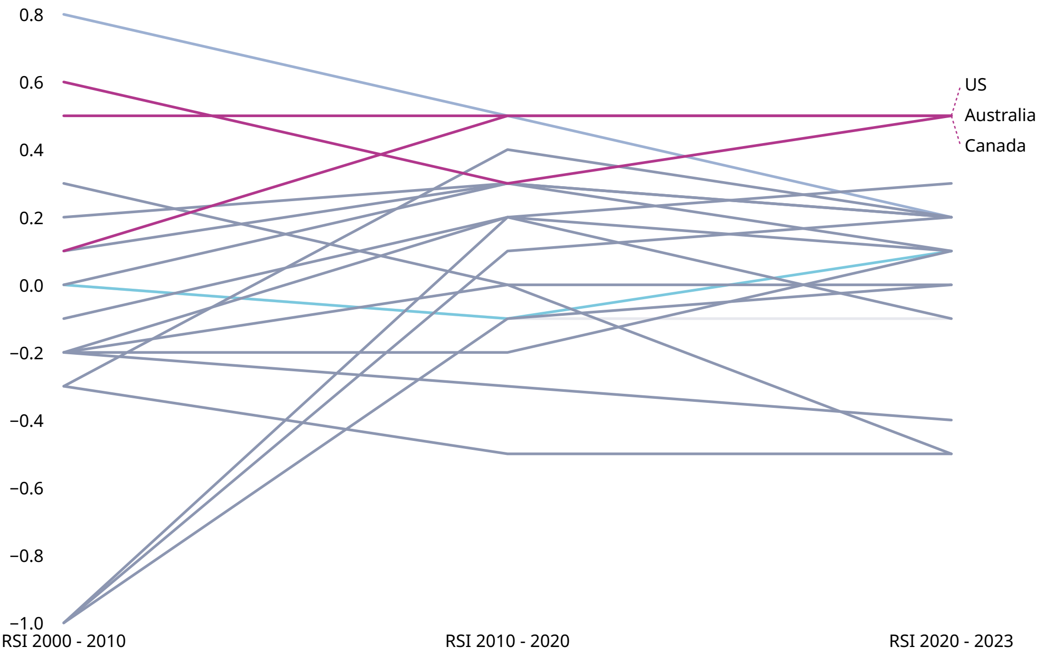
Notes: The size of the bubbles reflects the number of patent family publications at the country level in the field of Automation and Circularity. The CAGR are for 2018–2023, and the Relative Specialization Index (RSI) for the whole period analyzed, 2000–2023.

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Looking more closely at RSI values over the different time periods for a wider set of countries, Canada has the highest RSI values after 2020, followed by Australia and the United States (Figure D30). Ireland had a very high RSI score in the 2000s, but its score has fallen significantly over the last two decades.

Since 2020, Canada has had the highest RSI values, followed by Australia and the United States

Figure D30 Automation and Circularity: top 20 countries' RSI, 2000–2023



Note: RSI is relative specialization index.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Analysis of the top research countries in the different Automation and Circularity technologies reveals the following results (Figure D31):

- China has published by far the most patent family publications in smart production technologies. The United States is in second place.
- China also leads in patent families in space-related recycling applications. Japan is close behind in this field.
- The United States leads in patent family publications related to efficient material use.

China dominates patent family publications in smart production technologies, whereas the United States leads in efficient material use

Figure D31 Top 20 inventor locations for Automation and Circularity subgroups, 2000–2023

	Efficient Material Use Patent family publications 2000 - 2023	Recycling Patent family publications 2000 - 2023	Smart Production Patent family publications 2000 - 2023
China	134	25	1,877
US	164	14	879
Japan	13	20	202
Republic of Korea	8	6	146
Germany	46	2	122
Canada	9	7	59
UK	18	4	51
France	26	2	47
Australia	9	4	36
Israel	0	0	23
Russia	11	8	23
Sweden	1	0	21
India	2	2	20
Switzerland	2	0	15
Italy	5	0	15
Austria	1	1	14
Irland	0	1	10
Netherlands	5	0	10
Spain	2	1	9
New Zealand	2	1	6

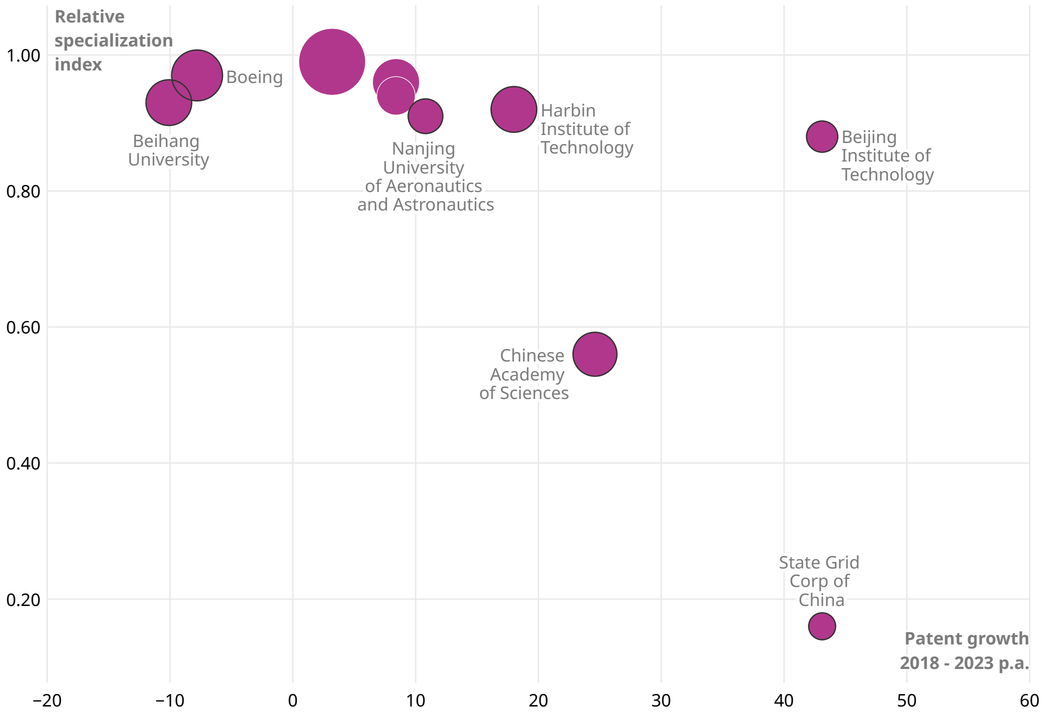
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

The list of top patent holders in space-related Automation and Circularity technologies is dominated by Chinese companies and research institutions. Eight of the top 10 patent holders are Chinese, led by China Aerospace Science and Technology Corporation (CASC), with 194 patent family publications between 2000 and 2023. Boeing (112 patent family publications) in second place and Airbus (63) in seventh place are the only non-Chinese companies among the top 10.

In terms of patent dynamics, the State Grid Corp of China and the Beijing Institute of Technology have achieved the highest growth rates since 2018.

China's companies and research institutions dominate Automation and Circularity technologies, with eight of the top 10 patent holders being Chinese

Figure D32 Automation and Circularity: comparison of top patent owners, RSI (2000–2023) and growth rates (2018–2023)



Note: RSI is relative specialization index.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

The top research players in the three Automation and Circularity subgroups are as follows (Figure D33):

- China Aerospace Science and Technology Corporation (CASC) is the research leader in space-related smart production technologies. For example, its subdivision, China Academy of Space Technology (CAST), develops lunar rovers for Chinese space missions.[7]
- Boeing and Airbus are the top research companies in the field of efficient material use. For example, Airbus has recently developed a metal 3D printer for the European Space Agency (ESA) that will be tested aboard the Columbus module of the International Space Station.[8] The goal is to deliver on-orbit manufacturing capabilities to space, enabling astronauts to directly manufacture tools that could connect several parts together.
- No clear patent leader exists in space-related recycling technologies. Several companies have like BAE Systems and Hitachi published two patent families in this field over the last years.

7 Space.com (2024). China just sent a secret mini-rover to the far side of the moon on its Chang'e 6 sample-return probe. Available at: www.space.com/china-change-6-moon-mission-mini-rover.
8 Airbus (2024). The world's first metal 3D printer for space is on its way to the ISS. Available at: www.airbus.com/en/newsroom/stories/2024-01-the-worlds-first-metal-3d-printer-for-space-is-on-its-way-to-the-iss.

CASC leads in space-related smart production technologies, while Boeing and Airbus excel in efficient material use research

Figure D33 Top 5 patent owners in the subgroups of Automation and Circularity, 2000 – 2023

Subgroup	Company	Patent family publications
Efficient material use	Arkema SA	8
Efficient material use	BAE Systems PLC	8
Efficient material use	RTX Corp	8
Efficient material use	Airbus SE	32
Efficient material use	Boeing Co	34
Recycling	Chinese Academy of Sciences CAS	2
Recycling	EchoStar Corp	2
Recycling	Hitachi Ltd	2
Recycling	Metso Corp	2
Recycling	BAE Systems PLC	2
Smart production	Boeing Co	97
Smart production	Beihang University	88
Smart production	Harbin Sinstitute of Technology	91
Smart production	Northwestern Polytechnical University	110
Smart production	China Aerospace Science and Technology Corporation (CASC)	187

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Communication and Security

Communication and Security technologies are vital for space exploration and operations. For any spacecraft, uninterrupted communication with Earth is paramount. Real-time data transmission allows mission control to monitor spacecraft health, receive scientific data and send critical commands. Reliable communication is also essential for the safety of the astronauts, enabling voice and video communication with Mission Control and providing a lifeline in case of emergency.

Security is another critical issue. Spacecraft, satellites and ground infrastructure are all vulnerable to cyberattacks that could potentially disrupt operations, steal sensitive data or even render the spacecraft inoperable.

In this report, Communication and Security technologies consist of the following five subcategories: device-to-device communication, navigation, cloud, low-latency communication, and cybersecurity.

By far the most important area in terms of patent family publications is low-latency communication. The number of patent family publications in this area has increased from 1,300 in 2000 to 8,217 in 2023 (Figure D34). Latency is the time delay over a communications link and is primarily determined by the distance data must travel between a user and the server.[9] In the context of space, traditional communication methods can suffer from significant delays due to the immense distances involved.

9 Telesat. Real-time latency: Rethinking remote networks. Available at: www.telesat.com/wp-content/uploads/2022/11/Real-Time-Latency.pdf.

Low-latency communication offers a significant advantage, by minimizing these delays. Advancements in technologies like laser communication and constellations of low-Earth orbit satellites are paving the way for a new era of low-latency communication.

The second most important research area is navigation technologies, where patent family numbers have grown from 266 to 1,704 between 2000 and 2023. Precise navigation is a critical element of any space mission. Complex calculations and tracking methods are used to determine a spacecraft's position, velocity and trajectory, allowing for course corrections, if necessary.

Patent family publications for device-to-device (D2D) communication in space applications have increased from 346 in 2000 to 643 in 2023. Currently, most space communication relies on a central hub – a satellite or ground station – that relays data between different devices. This approach can introduce delays and limitations, especially for missions venturing far from Earth. D2D communication offers a more direct approach whereby Spacecraft communicate with each other directly. This can significantly reduce communication delays, particularly for missions beyond the reach of Earth-based communication systems.

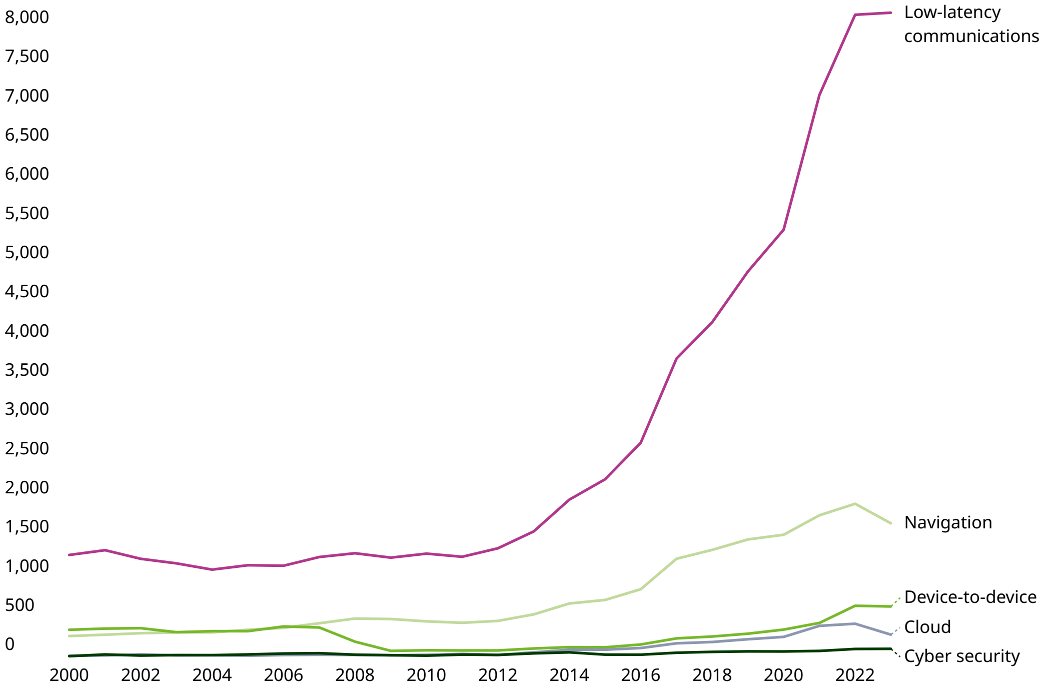
Patenting activity in the area of cloud technologies in space has expanded from 15 patent family publications in 2000 to 284 in 2023. In the context of space, cloud technologies can be broadly categorized into two approaches: ground-based cloud and space-based cloud. Ground-based cloud systems provide a way for spacecraft to offload data processing tasks.[10] By transmitting data to a ground-based cloud, scientists can access and analyze it in real or near-real time, accelerating research and decision-making. The space-based cloud, which is still in the early stages of development, involves creating a cloud infrastructure in space itself. This could take the form of constellations of small satellites or dedicated cloud platforms in orbit. While the technical challenges are significant, a space-based cloud offers the potential for on-demand computing power and data storage closer to the source.

Patent activity in space cybersecurity remains limited, with only 103 patent families published in 2023.

10 BIS Research (2023). Unlocking the potential of satellite-based cloud computing for space exploration. Available at: https://bisresearch.com/insights/unlocking-the-potential-of-satellite-based-cloud-computing-for-space-exploration.

Low-latency communication is the most significant area for patent family publications

Figure D34 Communication and Security: development of global patent family publications, 2000–2023

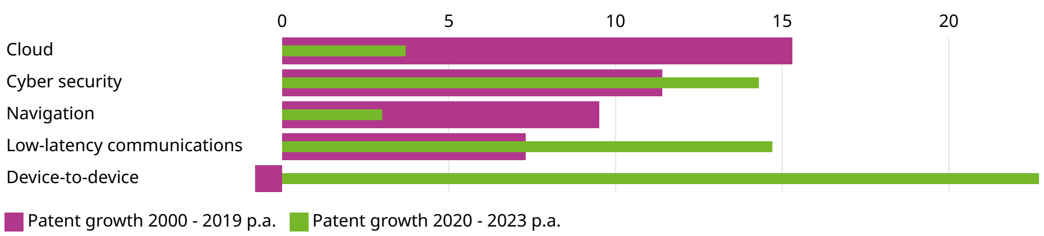


Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Innovation activity has been dynamic in most Communication and Security technologies over the last two decades (Figures D35–D37). Since 2020, patent growth rates have been particularly high for cybersecurity, device-to-device and low-latency communication patents (Figure D35).

Since 2020, cybersecurity, device-to-device, and low-latency communication patents have seen particularly high growth rates

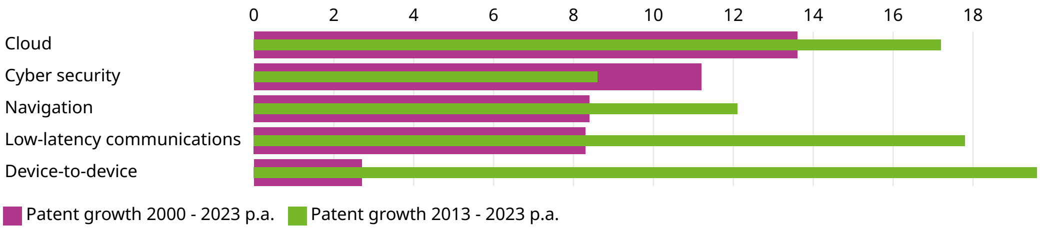
Figure D35 Communication and Security: growth of patent family publications, 2000–2019 and 2020–2023



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

There has been significant patent growth in cloud, device-to-device, and low-latency communication technologies

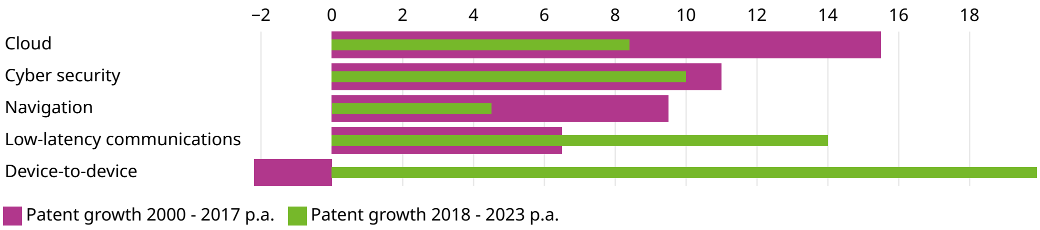
Figure D36 Communication and Security: growth of patent family publications, 2000–2023 and 2013–2023



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Device-to device communication technologies have grown significantly since 2018

Figure D37 Communication and Security: growth of patent family publications, 2000–2017 and 2018–2023



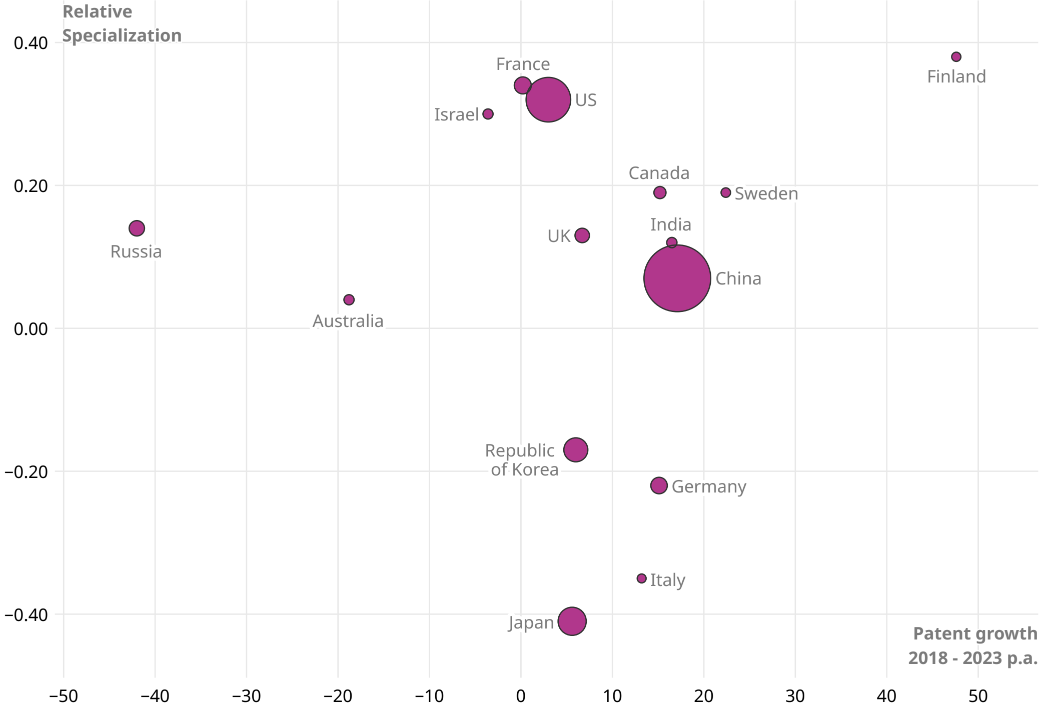
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Figure D38 shows that inventors from China are responsible for most patent family publications. In addition, the CAGR of patent family publications from China since 2018 is more than 17%, only Finland and Sweden have achieved even higher growth rates in recent years.

In terms of RSI, Finland, France, the United States and Israel have the highest values, indicating an above average degree of specialization.

China dominates patent family publications with a CAGR exceeding 17% since 2018, surpassed only by Finland and Sweden in terms of recent growth rate

Figure D38 Communication and Security: country comparison, RSI (2000–2023) and growth rates (2018–2023)



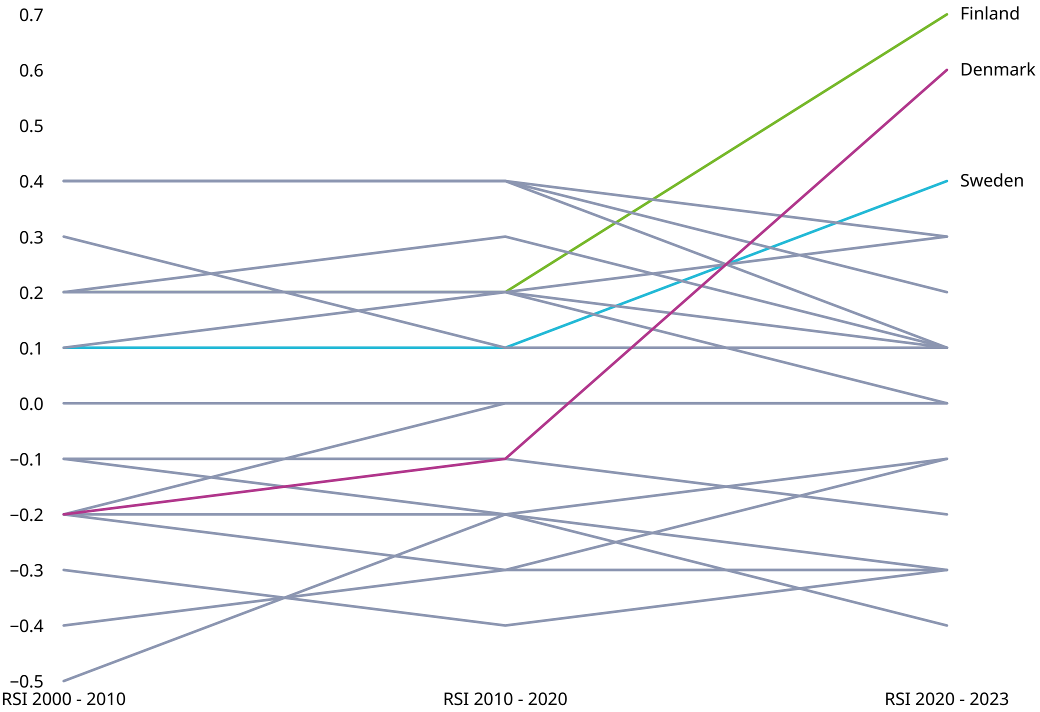
Notes: The size of the bubbles shows the number of patent family publications at the country level in the field of Communication and Security. The CAGR are for 2018–2023, and the Relative Specialization Index (RSI) for the whole period analyzed, 2000–2023.

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

A closer look at RSI values over the different time periods for a broader group of countries shows that Finland and Denmark have significantly increased their RSI values in space Communication and Security technologies over the last two decades (Figure D39). As a result, these two countries currently lead ahead of Sweden, Canada and the United States in the RSI ranking in the latest period, 2020–2023.

Finland and Denmark have markedly increased their RSI values in space communication and security technologies over the last two decades

Figure D39 Communication and Security: top 20 countries' RSI, 2000–2023



Note: RSI is relative specialization index.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Analysis of the top research countries in the different Communication and Security technologies reveals the following results (Figure D40):

- China has published the most patent family publications in low-latency communication, navigation technologies and space cloud applications.
- The United States leads in device-to-device patent family publications and in cybersecurity.
- Japan and the Republic of Korea are also important research locations in most communication technologies.

China tops patent family publications in low-latency communication, navigation technologies, and space cloud applications, while the United States leads in device-to-device patents and cybersecurity

Figure D40 Top 20 inventor locations for Communication and Security subgroups, 2000–2023

	Device-to-device 2000 - 2023	Navigation 2000 - 2023	Cloud 2000 - 2023	Cybersecurity 2000 - 2023	Low-latency-communication 2000 - 2023
China	1,803	8,792	1,533	385	34,584
US	3,085	4,538	809	477	15,377
Japan	665	1,778	85	59	5,751
Republic of Korea	614	1,315	64	34	4,168
France	228	503	28	30	1,929
Germany	261	602	42	23	1,671
Russia	21	553	2	7	1,300
UK	257	362	54	33	1,310
Canada	160	229	46	28	804
India	121	138	27	15	489
Australia	101	161	44	20	466
Israel	77	135	12	8	450
Sweden	130	95	10	5	358
Finland	102	100	5	1	326
Italy	20	94	5	2	262
Netherlands	41	62	7	1	206
Spain	31	49	7	5	192
Denmark	25	42	2	2	198
Switzerland	21	63	3	4	157
Austria	12	36	2	2	99

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

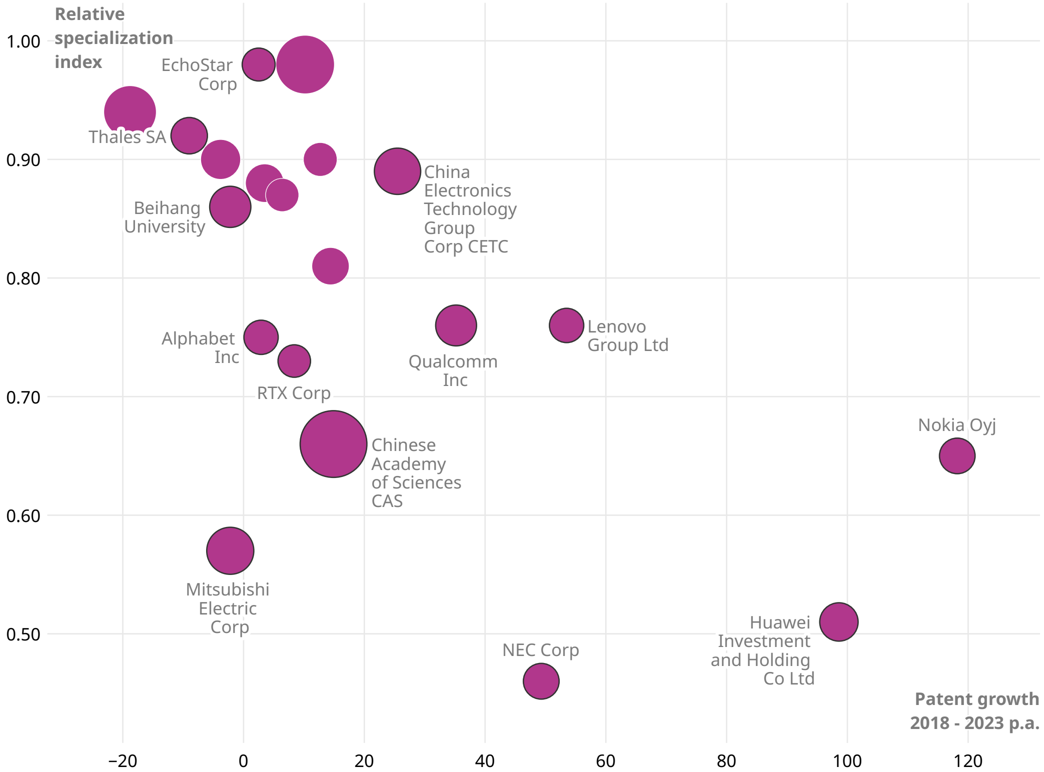
The Chinese Academy of Sciences, China Aerospace Science and Technology Corporation (CASC), Boeing, Mitsubishi Electric and China Electronics Technology Group are the leading research players in Communication and Security technologies for space applications (Figure D41).

In terms of patent dynamics, Nokia and Huawei have achieved the highest growth rates since 2018.

China Aerospace Science and Technology Corporation (CASC) has the highest RSI score, indicating a very high research specialization in Communication and Security technologies.

The Chinese Academy of Sciences, China Aerospace Science and Technology Corporation (CASC), and Boeing are the leading players in Communication and Security technologies for space applications

Figure D41 Communication and Security: comparison of top patent owners, RSI (2000–2023) and growth rates (2018–2023)



Note: RSI is relative specialization index.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

The top research players in the five subgroups are as follows (Figure D42):

- Qualcomm has developed 355 patent family publications in the field of device-to-device communications. This is twice as many as second ranked Boeing. Qualcomm has undertaken substantial research efforts in integrating satellite communication capabilities into mobile devices.[11] While Qualcomm's primary focus has been on integrating satellite communications into consumer devices, its expertise in wireless technologies provides a foundation for potential advances in device-to-device communications in space.
- The Chinese Academy of Sciences and China Aerospace Science and Technology Corporation (CASC) are the research leaders both in navigation technologies and low-latency communication.
- Boeing is ranked first in cybersecurity patent families.
- Alphabet is the owner of most patent family publications in space cloud applications.

11 Qualcomm (2023). Qualcomm launches new satellite IoT solutions to provide uninterrupted remote monitoring and asset tracking. Available at: www.qualcomm.com/news/releases/2023/06/qualcomm-launches-new-satellite-iot-solutions-to-provide-uninter.

Qualcomm excels in device-to-device communication, whereas Chinese institutions lead in navigation and low-latency communication

Figure D42 Top 5 patent owners in the subgroups of Communication and Security, 2000–2023

Subgroup	Company	Patent family publications
Device-to-device	AT&T Inc	134
Device-to-device	Nokia Oyj	148
Device-to-device	Huawei Investment and Holding Co Ltd	152
Device-to-device	Boeing Co	157
Device-to-device	Qualcomm Inc	355
Navigation	Mitsubishi Electric Corp	270
Navigation	Beihang University	359
Navigation	Boeing Co	398
Navigation	China Aerospace Science and Technology Corporation (CASC)	449
Navigation	Chinese Academy of Sciences CAS	453
Cloud	Baidu Inc	19
Cloud	Microsoft Corp	20
Cloud	Boeing Co	23
Cloud	Chinese Academy of Sciences CAS	41
Cloud	Alphabet Inc	59
Cybersecurity	EchoStar Corp	18
Cybersecurity	Honeywell International Inc	18
Cybersecurity	Huawei Investment and Holding Co Ltd	31
Cybersecurity	Alphabet Inc	41
Cybersecurity	Boeing Co	62
Low-latency communication	Mitsubishi Electric Corp	999
Low-latency communication	China Electronics Technology Group Corp CETC	1,004
Low-latency communication	Boeing Co	1,164
Low-latency communication	China Aerospace Science and Technology Corporation (CASC)	1,392
Low-latency communication	Chinese Academy of Sciences CAS	2,057

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Human–Machine Interface

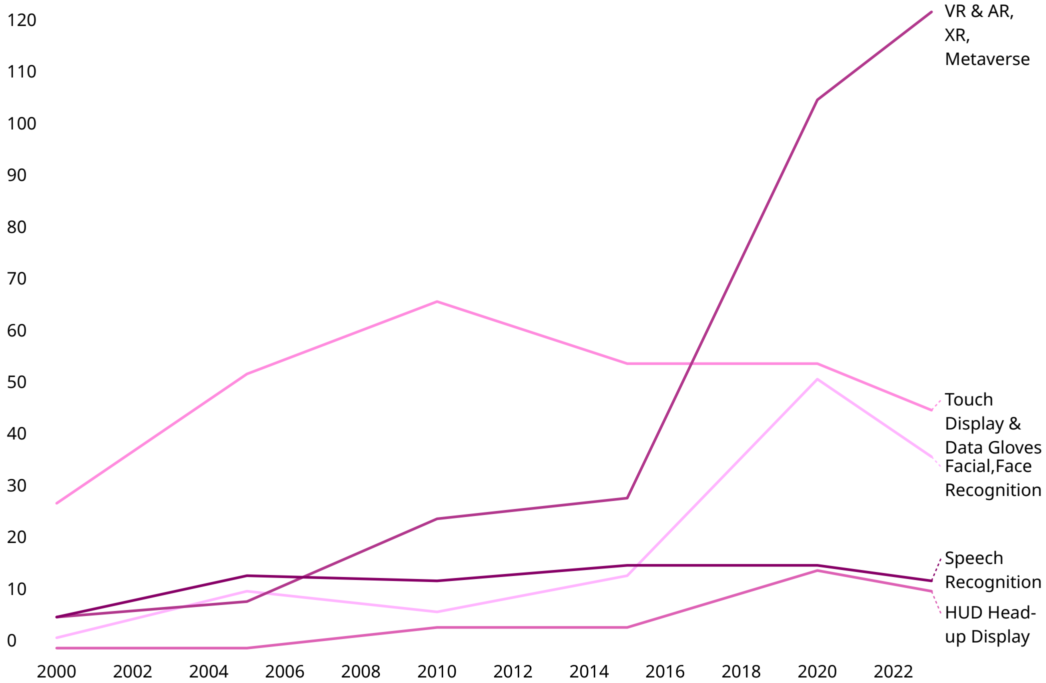
Human–Machine Interface (HMI) technologies enable astronauts and ground control teams to better interact with complex spacecraft systems. Such interfaces must be intuitive, reliable, compact and adaptable to the unique challenges of the space environment.

In this report, HMI technologies consist of the following subcategories: VR/AR/metaverse, touch displays/data gloves, facial/face recognition, voice recognition and head-up displays.

In terms of patenting activity, VR/AR/metaverse is the key subgroup, with a strong increase in published patent families in recent years, reaching 124 publications in 2023 (Figure D43). Virtual reality (VR) and augmented reality (AR) technologies offer potential benefits for training, mission planning and remote operations. Touch displays/data gloves are increasingly used to optimize interactions within the spacecraft. Patenting activity in this area has been volatile, reaching 47 patent family publications in 2023. The number of patent families dealing with facial/face recognition technologies has risen sharply since 2000, although patenting activity has recently declined after peaking in 2021. Patenting activity in space-related speech recognition and head-up displays has remained modest.

VR/AR/metaverse is a rapidly growing field, as evidenced by the significant increase in recent patent filings

Figure D43 Human–Machine Interface: development of global patent family publications, 2000–2023

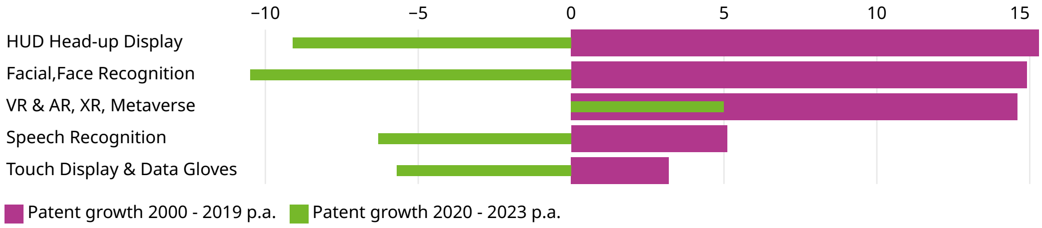


Note: VR is virtual reality, AR is augmented reality, and XR is extended reality.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Over different time periods, innovation dynamics in HMI technologies have been mixed (Figures D44–D46). While patenting increased in all technologies from 2000 to 2019, it decreased considerably from 2020 onward (Figure D43). The sole exception is VR/AR/metaverse, where global patent family publications continue to grow.

Patent activity increased across all technologies from 2000 to 2019, but has significantly declined since 2020

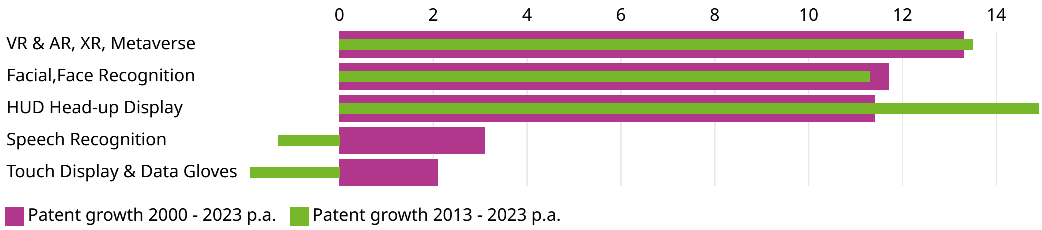
Figure D44 Human–Machine Interface: growth of patent family publications, 2000–2019 and 2020–2023



Note: VR is virtual reality, AR is augmented reality, and XR is extended reality.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Head-up Display has shown the strongest growth since 2013

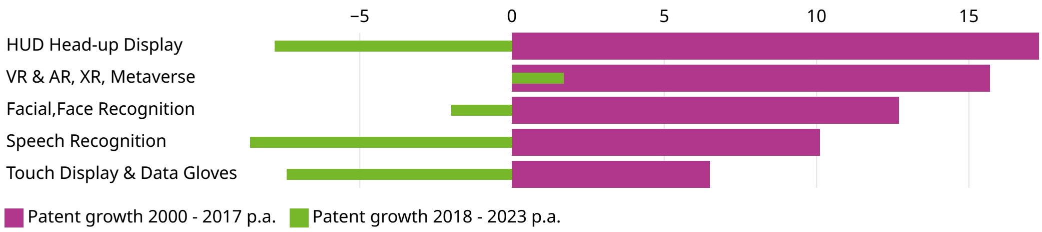
Figure D45 Human–Machine Interface: growth of patent family publications, 2000–2023 and 2013–2023



Note: VR is virtual reality, AR is augmented reality, and XR is extended reality.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Whereas HMI technology innovation has fluctuated, VR/AR/metaverse continues to see strong patent growth

Figure D46 Human–Machine Interface: growth of patent family publications, 2000–2017 and 2018–2023



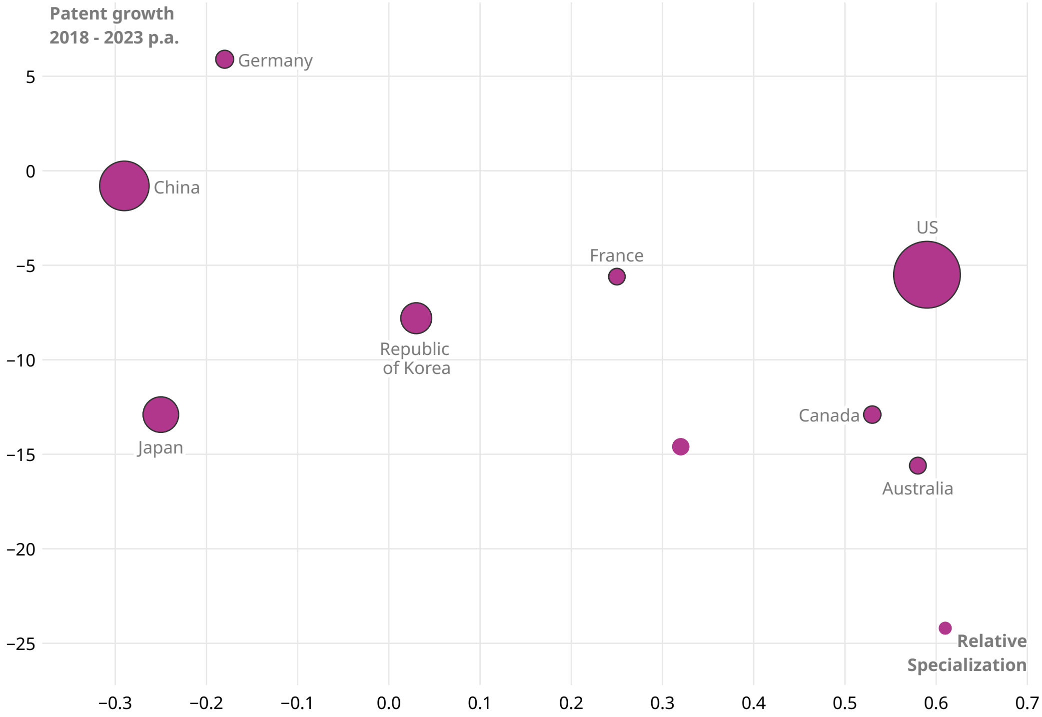
Note: VR is virtual reality, AR is augmented reality, and XR is extended reality.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Figure D47 shows that US inventors responsible for the majority of patent family publications. The United States also has one of the highest RSI values, together with Israel, Canada and Australia, indicating an above average degree of specialization.

In terms of patent growth, Germany outperforms all other locations, with an average annual growth rate of 5.9% in patent family publications since 2018. Patent growth in all other major inventor countries has been negative since 2018.

Germany leads in patent growth, with an average annual increase of 5.9% since 2018

Figure D47 Human–Machine Interface: Country comparison, RSI (2000–2023) and growth rates (2018–2023)



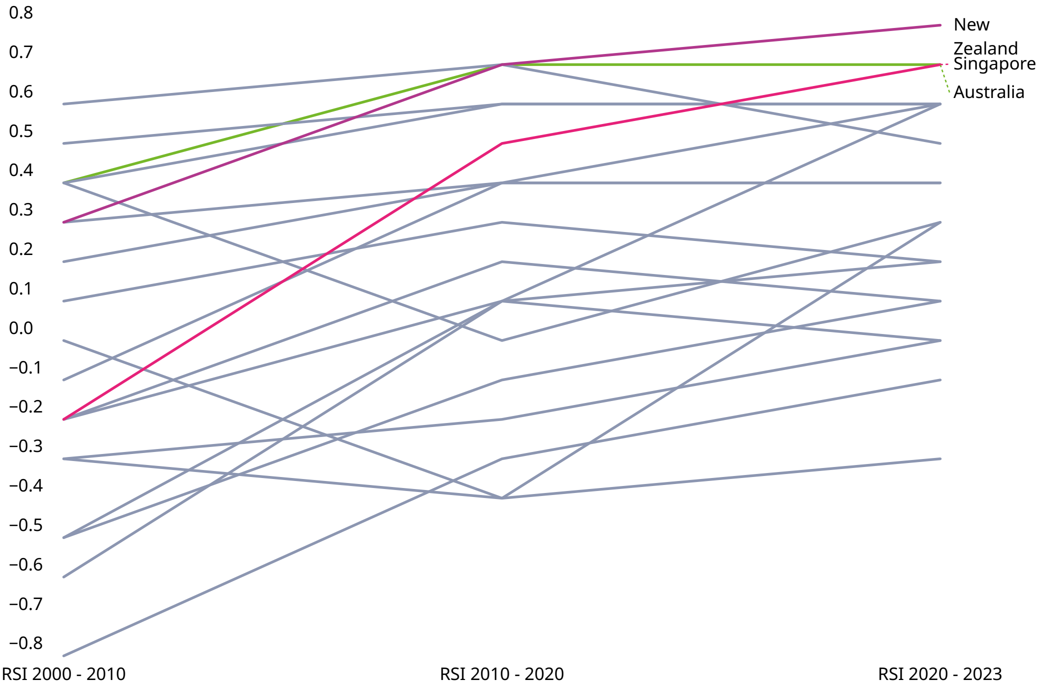
Note: The size of the bubbles reflect the number of patent family publications at the country level in the field of HMI technologies. The CAGR are for 2018–2023, and the Relative Specialization Index (RSI) for the whole period analyzed, 2000–2023.

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Looking more closely at RSI values over the different time periods for a wider group of countries, New Zealand has the highest RSI score after 2020, followed by Singapore and Australia (Figure D48). In contrast, China has a clearly negative RSI, indicating a below average specialization in research on space-related HMI technologies.

New Zealand, Singapore and Australia have the highest RSI scores after 2020

Figure D48 Human–Machine Interface: top 20 countries' RSI, 2000–2023



Note: RSI is relative specialization index.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

An analysis of the top research countries in the different HMI technologies reveals the following results (Figure D49):

- The United States has published the most patent family publications in all five HMI technology fields. The technological lead of the United States is particularly high in touch displays/data gloves.
- China is in second place in most HMI technologies, but Japan is almost at an equal level in touch displays/data gloves and surpasses China in head-up display patent family publications.

The United States leads in patent family publications across all five HMI technology fields

Figure D49 Top inventor locations for Human–Machine Interface subgroups, 2000–2023

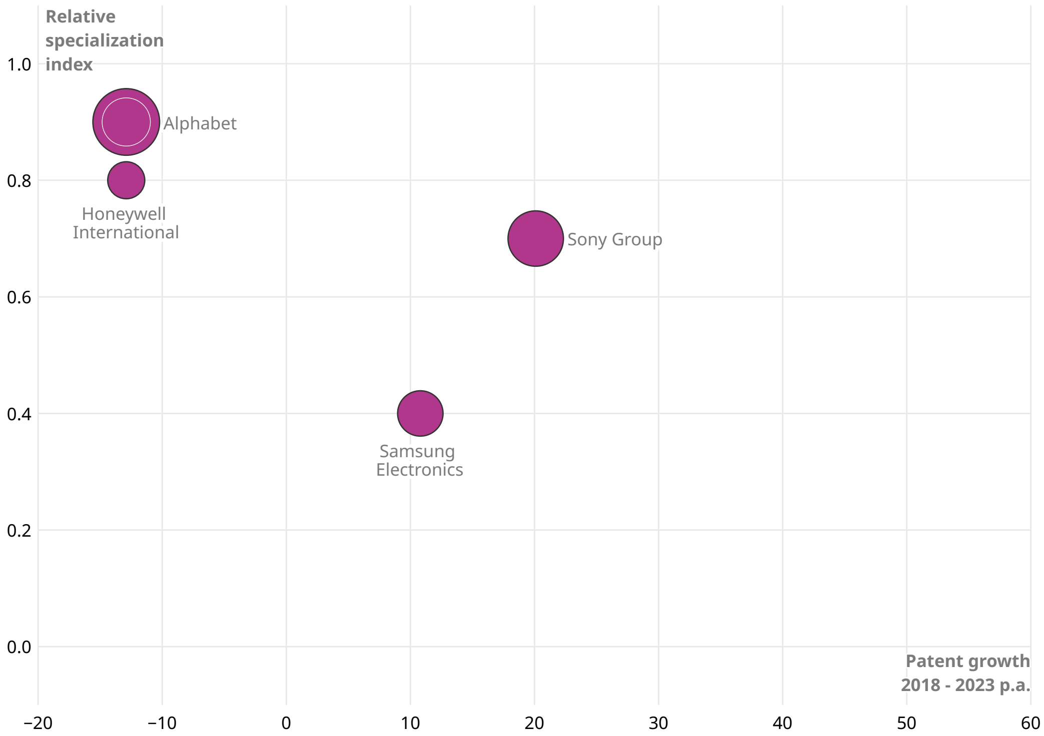
	Face Recognition Patent family publications 2000 - 2023	VR/metaverse Patent family publications 2000 - 2023	Touch display&data gloves Patent family publications 2000 - 2023	Head-up display Patent family publications 2000 - 2023	Speech recognition Patent family publications 2000 - 2023
US	256	437	627	74	223
China	128	300	239	12	115
Japan	42	99	212	35	35
Republic of Korea	25	132	117	15	24
Germany	15	38	36	10	8
Israel	13	20	11	6	9
Canada	13	29	44	8	13
UK	13	33	37	6	15
Australia	11	18	42	1	11
India	8	13	11	2	7
France	5	26	31	8	7
Netherlands	4	10	12	3	4
Taiwan	4	5	26	0	1
Sweden	3	7	6	2	1
New Zealand	2	0	6	0	0
Finland	2	8	3	1	0
Switzerland	2	6	5	1	4
Singapore	1	8	2	0	0
Italy	1	5	12	1	0
Greece	0	5	0	0	2
Russia	0	11	5	2	0

Note: VR is virtual reality.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Alphabet leads the list of the four top patent holders in space-related HMI technologies, with 83 patent family publications since 2000 (Figure D50). However, Alphabet's patenting activity in this field has declined over recent years. The same is true for third-ranked Boeing (43 patent family publications). In contrast, Sony (ranked second, with 57 patent family publications) and Samsung Electronics (ranked fourth, with 38 patent family publications) have achieved positive growth rates since 2018.

Alphabet has been the top patent holder in space-related HMI technologies since 2000, but its patent activity has decreased recently

Figure D50 Human–Machine Interface: comparison of top patent owners, RSI (2000–2023) and growth rates (2018–2023)



Note: RSI is relative specialization index.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

The top patent owners in the HMI subgroups are as follows (Figure D51):

- Alphabet has published more than 60 patent families in touch displays/data gloves and nine in speech recognition, leading both rankings.
- Sony Group, Samsung Electronics and Boeing are research leaders in AR/VR/metaverse, with more than 20 patent family publications each.
- Tata Consultancy and SoftBank lead in facial recognition technologies.
- Denso and RTX top the list for head-up displays.

Alphabet leads in touch displays/data gloves and speech recognition, whereas Sony, Samsung, and Boeing are research leaders in AR/VR/metaverse

Figure D51 Top 5 patent owners in the subgroups of Human–Machine Interface, 2000–2023

Subgroup	Company	Patent family publications
Facial recognition	Nippon Telegraph and Telephone	8
Facial recognition	RTX	8
Facial recognition	Volkswagen	8
Facial recognition	SoftBank Group	9
Facial recognition	Tata Consultancy Services	9
VR/Metaverse	Alphabet	13
VR/Metaverse	DJI	15
VR/Metaverse	Boeing	20
VR/Metaverse	Samsung Electronics	22
VR/Metaverse	Sony Group	23
Touch display and data gloves	Microsoft	16
Touch display and data gloves	Huawei Investment and Holding	21
Touch display and data gloves	Boeing	28
Touch display and data gloves	Sony Group	40
Touch display and data gloves	Alphabet	63
Head-up display	Airbus	4
Head-up display	Boeing	4
Head-up display	LG Electronics	5
Head-up display	RTX	8
Head-up display	Denso	14
Speech recognition	Echostar	4
Speech recognition	Panasonic Holdings	5
Speech recognition	AT&T	7
Speech recognition	Intellectual Ventures	7
Speech recognition	Alphabet	9

Note: VR is virtual reality.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Emerging technology in detail: additive manufacturing in space

Additive manufacturing (AM) in space, often referred to as in-situ manufacturing, is the process of creating objects layer by layer directly in the space environment.[1] Unlike traditional manufacturing, which often involves subtracting material from a larger block, AM builds objects, by adding material only where necessary. This technology encompasses various methods such as 3D printing, which uses materials like polymers, metals and even lunar regolith to create the tools, components and structures required for space missions. AM in space is defined by its ability to utilize locally available resources (like regolith on the Moon or Mars) and by the constraints of the space environment such as microgravity and vacuum conditions.[2] This technology aims to support long-term space missions, by reducing dependency on Earth-supplied materials and enhancing the sustainability of space exploration.

AM in space is relevant for several reasons. Traditional space missions are constrained by the size of the launch vehicle's fairing, which limits the size and volume of equipment that can be sent to space. AM enables the creation of larger structures directly in space, bypassing these limitations.[3] Transporting materials and parts from Earth to space is extremely costly. AM can significantly reduce these costs, by allowing the production of necessary components on-site, thus minimizing the frequency and cost of resupply missions. For long-term missions, such as those to Mars, the ability to manufacture tools, parts and even habitats on-site is crucial. This capability reduces the need to carry extensive spare parts and allows for more flexible and extended missions.[4] Moreover, the ability to produce large structures like solar arrays, antennas and habitat modules in space opens up new possibilities for mission designs that were previously impractical or impossible due to size and weight constraints.[5]

Several types of AM techniques are being developed and utilized in space. Polymer additive manufacturing involves the use of polymers to create tools and parts. For instance, the POP3D system developed by the Italian Space Agency and ESA's manufacturing of experimental layer technology (MELT) printer can produce parts using high-strength thermoplastics like PEEK (polyether ether ketone).[6] AM technologies are also being developed to enable metal printing in space such as wire-based direct energy deposition methods. This technique allows for the creation of the strong and durable components necessary for various space applications. Another method is regolith-based manufacturing, which uses lunar or Martian regolith to create structures. Techniques include binder jetting and sintering using solar energy. For example, ESA has demonstrated the use of regolith simulant with magnesium chloride binders and solar sintering to create structural elements.[7] Bioprinting in space involves creating living tissue and

1 Sacco, E. and S. K. Moon (2019). Additive manufacturing for space: Status and promises. The International Journal of Advanced Manufacturing Technology, 105, 4123–4146.
2 Prater, T., J. Edmunson, M. Fiske, F. Ledbetter, C. Hill, M. Meyyappan et al. (2019). NASA's in-space manufacturing project: Update on manufacturing technologies and materials to enable more sustainable and safer exploration. In 70th International Astronautical Congress (IAC), October (No. IAC-19. D3. 2B. 5).
3 Prater, T., J. Edmunson, M. Fiske, F. Ledbetter, C. Hill, M. Meyyappan et al. (2019). NASA's in-space manufacturing project: Update on manufacturing technologies and materials to enable more sustainable and safer exploration. In 70th International Astronautical Congress (IAC), October (No. IAC-19. D3. 2B. 5).
4 Zocca, A., J. Wilbig, A. Waske, J. Günster, M. P. Widjaja, C. Neumann et al. (2022). Challenges in the technology development for additive manufacturing in space. Chinese Journal of Mechanical Engineering: Additive Manufacturing Frontiers, 1(1), 100018.
5 Makaya, A., L. Pambaguian, T. Ghidini, T. Rohr, U. Lafont and A. Meurisse (2023). Towards out of earth manufacturing: Overview of the ESA materials and processes activities on manufacturing in space. CEAS Space Journal, 15(1), 69–75.
6 Makaya, A., L. Pambaguian, T. Ghidini, T. Rohr, U. Lafont and A. Meurisse (2023). Towards out of earth manufacturing: Overview of the ESA materials and processes activities on manufacturing in space. CEAS Space Journal, 15(1), 69–75.
7 Wang, Y., L. Hao, Y. Li, Q. Sun, M. Sun, Y. Huang et al. (2022). In-situ utilization of regolith resource and future exploration of additive manufacturing for lunar/Martian habitats: A review. Applied Clay Science, 229, 106673.

possibly organs. ESA has explored bioprinting using bio-inks that could include human blood plasma and other readily available substances in a space mission scenario. [8]

The benefits of AM in space are manifold. AM allows for the production of parts and tools as needed, reducing the need for carrying a large inventory of spares. [9] By manufacturing items in space, the overall mass that needs to be launched from Earth is reduced, leading to cost savings. AM enables the creation of complex geometries that would be difficult or impossible to achieve with traditional manufacturing methods. Using local resources like regolith for manufacturing reduces dependency on Earth, supporting more sustainable exploration missions. [10] Larger and more complex structures can be built in space, improving the performance and capabilities of spacecraft and habitats.

Despite its potential, AM in space faces several limitations and challenges. Assuring that materials printed in space have the same properties and performance as those manufactured on Earth is a significant challenge, especially under the harsh conditions of space that include extreme temperatures and radiation. [11] Space presents unique environmental challenges, including microgravity and vacuum conditions. These factors can affect the printing process and the quality of the produced parts. For regolith-based manufacturing, the quality and composition of lunar or Martian soil must be suitable for construction. Processes also need to be developed to efficiently extract and utilize these materials. [12] Many AM technologies are still at the developmental stage and require further testing and validation in order to assure they are reliable and safe enough for use in space missions. New manufacturing technologies must be integrated with existing spacecraft systems and operations, which can be complex and require significant modifications to current designs and processes.

Additive manufacturing in space: scientific publications

The scientific community has shown increasing interest in AM in space, as evidenced by the growing number of publications on the topic.

Figure D52 depicts the number of scientific documents published annually in the field of AM in space from 2014 to 2024. Several notable trends can be identified. Initially, this field experienced a slow growth rate from 2014 to 2015 indicating the nascent stages of research and foundational studies during this time. The number of publications began to rise significantly around 2016–2017, reflecting an increase in interest and early development efforts. This period likely marks the transition from exploratory research to more focused studies and early applications.

A notable dip appears in 2020, followed by a sharp increase. This surge suggests a period of accelerated research and significant advancements, possibly driven by technological breakthroughs, increased funding and heightened interest from both academia and industry. The subsequent years show a high level of activity, with another peak in 2023. Although has been a slight decline in 2024, the number of publications remains relatively high compared to the early years, indicating sustained interest and ongoing research efforts in the field.

8 ESA (2019). Upside-down 3D-printed skin and bone, for humans to Mars. European Space Agency. Available at: www.esa.int/Enabling_Support/Space_Engineering_Technology/Upside-down_3D-printed_skin_and_bone_for_humans_to_Mars.
9 Makaya, A., L. Pambaguian, T. Ghidini, T. Rohr, U. Lafont and A. Meurisse (2023). Towards out of earth manufacturing: Overview of the ESA materials and processes activities on manufacturing in space. CEAS Space Journal, 15(1), 69–75.
10 Isachenkov, M., S. Chugunov, I. Akhatov and I. Shishkovsky (2021). Regolith-based additive manufacturing for sustainable development of lunar infrastructure: An overview. Acta Astronautica, 180, 650–678.
11 Makaya, A., L. Pambaguian, T. Ghidini, T. Rohr, U. Lafont and A. Meurisse (2023). Towards out of earth manufacturing: Overview of the ESA materials and processes activities on manufacturing in space. CEAS Space Journal, 15(1), 69–75.
12 Farries, K. W., P. Visintin, S. T. Smith and P. van Eyk (2021). Sintered or melted regolith for lunar construction: State-of-the-art review and future research directions. Construction and Building Materials, 296, 123627.

Publications began to rise significantly around 2016–2017, reflecting an increase in interest and early development efforts

Figure D52 Development of global scientific publications related to additive manufacturing in space, 2014–2024

Source: WIPO, based on publication data from EconSight/Scopus, October 2024.

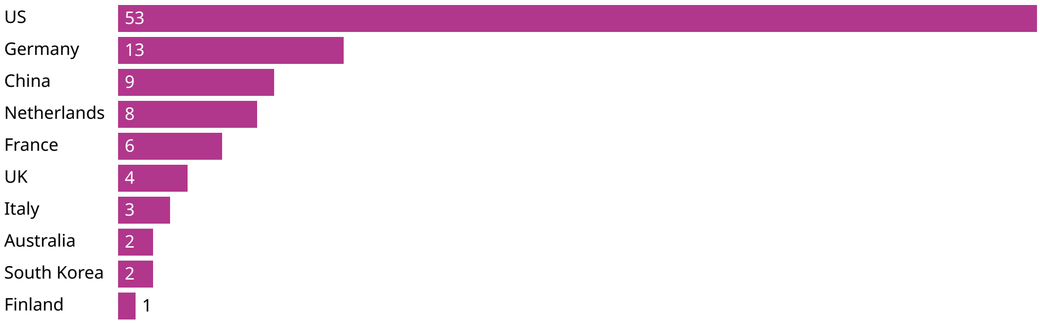
Figure D53 showing origin countries for scientific publications provides insights into the geographical distribution of research activity and highlights the leading contributors globally. The United States stands out as the dominant country in the field, with the highest number of publications. This dominance reflects significant investment in space technologies and a strong research infrastructure supporting advancements in AM. Germany follows, with substantial contributions indicating robust academic and industrial research capabilities in the country.

China is also a major player, with a considerable number of publications. This highlights China's growing focus on space exploration and advanced manufacturing technologies, driven by national initiatives and substantial funding. The Kingdom of the Netherlands and France have notable numbers of publications, signifying active research communities and potential collaborative projects within Europe.

Other countries, including the United Kingdom, Italy, Australia, the Republic of Korea and Finland, also contribute to the field, though to a lesser extent. This diverse but concentrated research effort underscores the global interest and collaborative nature of advancements in AM in space.

The United States is the dominant country in the field, with the highest number of publications

Figure D53 Origin countries for scientific publications related to additive manufacturing in space, 2000–2023



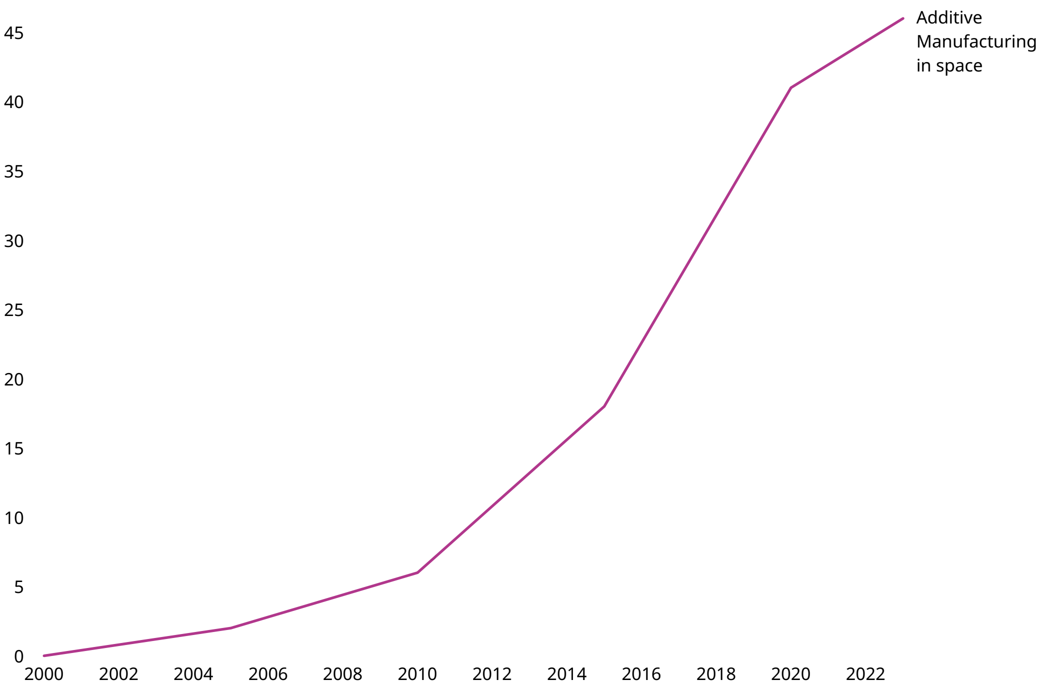
Source: WIPO, based on publication data from EconSight/Scopus, October 2024.

Additive manufacturing in space: patent data

The examination of the patent landscape reveals that patenting activity in the field of AM in space has picked up speed over the last years. The number of published patent families has increased from only 10 in 2014 to 46 in 2023 (Figure D54).

Recent years have seen upsurge in patenting activity related to Additive Manufacturing (AM) in space

Figure D54 Development of global patent family publications related to additive manufacturing in space, 2000–2023



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

The United States leads the country ranking for AM in space research, with 141 patent families published since 2000 (Figure D55). China, Germany, France and the United Kingdom are other important research locations.

The United States and China lead the country ranking for AM in space research

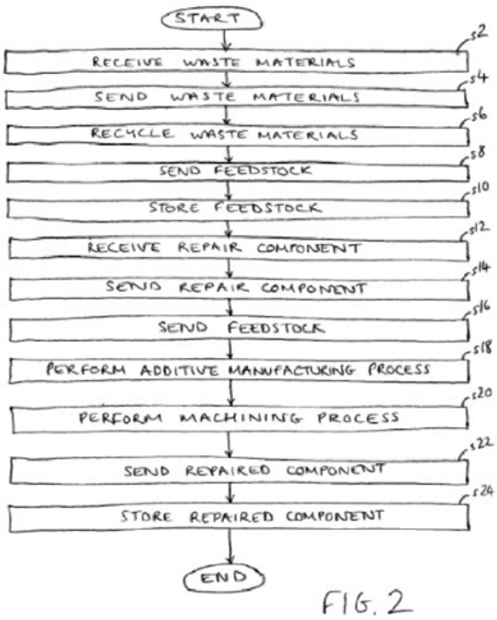
Figure D55 Patent family publications related to additive manufacturing in space, 2000–2023

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Additive manufacturing in space: patent examples

In 2019 BAE Systems developed early AM systems in space. The invention (EP3527373A1) pertains to an advanced system for manufacturing articles in space, integrated into a space-based object such as a space vehicle or station. The core component is an AM apparatus that uses supplied feedstock to produce various articles. This apparatus is supported by a feedstock storage module, ensuring a steady material supply, and a controller that manages the manufacturing operations.

A key feature is the recycling module, which converts waste material into usable feedstock, enhancing sustainability and efficiency, by minimizing waste and reducing the need for new materials. Additionally, the system includes a machining apparatus for further processing, with waste from both AM and machining being recycled.



Source: EP3527373A1.

The space-based object can dock with other objects, allowing the exchange of waste materials and manufactured or repaired articles, facilitating resource sharing in space missions. A storage module holds articles for repair, which the manufacturing apparatus can process, thus extending the life of critical components.

An inspection module assures the quality of manufactured articles, and the system can communicate with an Earth-based facility for data transfer and remote control. The manufacturing apparatus is versatile, capable of using wire, plastic or metal feedstock, making it adaptable for a variety of needs. Designed to be autonomous or remotely controlled, this system represents a significant advancement in in-space manufacturing, supporting long-term missions with improved efficiency and sustainability.

While the BAE invention focuses on focuses on sustainable manufacturing with integrated recycling, a patent from Made in Space Inc. (EP16857937A) put an emphasis on advanced assembly and integration capabilities in a space environment.

The invention pertains to a system and methods for in-space manufacturing and assembly of spacecraft devices and techniques. This system is designed to produce objects in a space environment, incorporating several innovative components to assure efficient and effective manufacturing processes.

At its core, the system includes a build device equipped with a build area and a material bonding component. This component receives portions of the material used to fabricate the object. Within the build area, at least one gripper contacts the object to provide support and serve as a heat sink, cooler or electrical dissipation path for the object. The build device also features a movement mechanism that positions the device relative to the object during production.

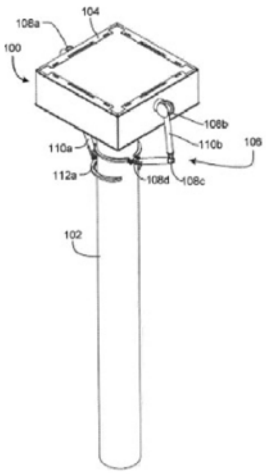


FIG. 1

Source: EP16857937A.

An additional feature of the system is its ability to operate within an infinite build area on at least one manufacturing axis, allowing the construction of objects larger than the build device itself. The system also integrates a knitted component for creating a web applied to the object during manufacturing, thus enhancing structural integrity.

The system's versatility is further demonstrated by its inclusion of an antenna element release mechanism, which allows for the extrusion and integration of antenna elements into the object. This capability ensures the seamless assembly of complex spacecraft components. To enhance functionality, the system comprises a robot arm designed to reach and manipulate distal portions of the object, a z-traverse system incorporating the gripper, and a buffer mechanism to manage the effects of gravity center movement in microgravity environments. The build device can either remain attached to the completed object, providing functional elements, or detach once the object is finished.

Additionally, the system supports the construction of spacecraft components and structures using AM materials by an extended structural additive manufacturing machine (ESAMM) device. This ESAMM device also facilitates the inspection, assembly and integration of electronic components and assembly accessories to form a complete spacecraft system.

The method associated with this system involves using the space or microgravity environment to construct spacecraft components, dissipate heat, conduct electricity and assure the structural integrity of the object during and after manufacturing. The process includes inspecting the components during construction, installing solar panels, forming antennas and repeating those steps to build multiple systems of the spacecraft. Overall, this invention represents a significant advancement in in-space manufacturing, offering comprehensive solutions for producing, assembling and integrating complex spacecraft components directly in the space environment.

Emerging technology in detail: blockchain in satellite communications

Blockchain technology in satellite communication represents a transformative approach to enhancing the security, efficiency and management of satellite networks. [1] Defined as the use of decentralized digital ledgers to manage and secure data exchanges and operational commands, blockchain in satellite communication leverages distributed ledger technology, smart contracts and advanced encryption methods to create a robust and secure communication network for satellites. This decentralized structure prevents single points of failure, making it harder for adversaries to disrupt or manipulate communication channels and assuring secure data transfer across space networks.

Alternative cybersecurity technologies that could be employed alongside or in place of blockchain include quantum encryption and artificial intelligence (AI)-driven anomaly detection. Quantum encryption uses quantum keys that are theoretically impossible to replicate, thus enhancing data protection between satellites. Meanwhile, AI-driven anomaly detection monitors satellite behavior to detect suspicious activity and potential threats in real time, offering an adaptive and proactive layer of defense. Such technologies may not, however, offer the same degree of decentralized trust and traceability that blockchain provides, making blockchain a uniquely effective choice for the current and evolving needs of space communication networks.

Blockchain technology is highly relevant to satellite communication owing to its ability to address critical security challenges. [2] Satellite communication systems are inherently vulnerable to hacking, interception and unauthorized access, because of their reliance on wireless transmission and distributed architecture. Blockchain provides a tamper-proof method of managing data and command transmissions, by ensuring that all transactions are transparent, verifiable and immutable. This significantly enhances the security of satellite communications, protecting sensitive data from potential cyber threats. A blockchain-based authentication and privacy protection scheme involves registration, authentication and revocation processes managed by a Ground Base Station (GBS), which records all key parameters on the blockchain, effectively securing the network against unauthorized access. [3]

The efficiency of satellite network management is also greatly improved through the use of blockchain. In satellite constellations and swarms, where multiple satellites need to communicate and coordinate their activities, blockchain can automate and streamline such processes. [4] Smart contracts can reduce latency and improve response times for satellite-to-satellite and ground-to-satellite communications, by automating routine tasks and ensuring that all nodes within a network have synchronized and up-to-date information. [5]

1 de La Beaujardiere, J., R. Mital and R. Mital (2019). Blockchain application within a multi-sensor satellite architecture. In IGARSS 2019-2019 IEEE International Geoscience and Remote Sensing Symposium, July. Institute of Electrical and Electronics Engineers, 5293–5296.
2 Wang, Y., Z. Su, J. Ni, N. Zhang and X. Shen (2021). Blockchain-empowered space-air-ground integrated networks: Opportunities, challenges, and solutions. IEEE Communications Surveys and Tutorials, 24(1), 160–209.
3 Li, C., X. Sun and Z. Zhang (2021). Effective methods and performance analysis of a satellite network security mechanism based on blockchain technology. IEEE Access, 9, 113558–113565.
4 Pham, Q. V., R. Ruby, F. Fang, D. C. Nguyen, Z. Yang, M. Le et al. (2022). Aerial computing: A new computing paradigm, applications, and challenges. IEEE Internet of Things Journal, 9(11), 8339–8363.
5 Torky, M., T. Gaber, E. Goda, V. Snasel and A. E. Hassanien (2022). A blockchain protocol for authenticating space communications between satellites constellations. Aerospace, 9(9), 495.

Additionally, blockchain technology enables the creation of secure and virtual trusted zones in space. This capability is crucial for the management and operation of satellite swarms, which require precise coordination and secure data sharing across different orbits. By using blockchain, satellite operators can assure that all communications within the swarm are secure and that any data shared is authentic and has not been tampered with. [6]

There are several types of blockchain implementation in satellite communication, according to de La Beaujardiere and colleagues. [7] One common type involves using satellites as nodes within a blockchain network, where they participate in the validation and recording of transactions. This decentralized approach allows for a more secure and efficient management of satellite operations. Another implementation involves satellites acting as validators or miners, verifying transactions and adding them to the blockchain. This assures the integrity and accuracy of the data recorded. Additionally, satellites can request that specific data transactions are stored on the blockchain, providing a secure method for storing and retrieving critical information. Various communication models, such as satellite-to-satellite, ground station-to-satellite, user-to-satellite and ground station-to-ground station, can also be facilitated through blockchain, automating and securing these interactions.

The integration of blockchain in satellite communication offers numerous benefits. Enhanced security is one of the most significant, with blockchain providing robust encryption, tamper-proof records and decentralized control that collectively reduce the risk of unauthorized access and cyberattack. [8] Improved efficiency is another key benefit, as blockchain can automate various communication processes through smart contracts, reducing the need for manual intervention and speeding up data verification and transmission. Furthermore, blockchain assures the transparency and traceability of all transactions, thus maintaining the integrity of satellite operations and assuring accountability among stakeholders. [9] The decentralized nature of blockchain eliminates single points of failure, enhancing the reliability and resilience of satellite communication networks.

However, the application of blockchain in satellite communication is not without challenges. Satellites have limited computational power, storage capacity and energy resources, which can constrain the implementation of blockchain technology that typically requires significant computational resources. [10] Latency issues also pose a challenge; although blockchain can reduce some types of latency, the time required to validate and add transactions to the blockchain can affect real-time communication. [11] Scalability is another concern, as the increase in transactions and nodes in the blockchain network can lead to slower processing times and higher operational costs. [12] Additionally, integrating blockchain with existing satellite communication protocols and systems can be complex, requiring significant modifications and adaptations to ensure seamless operation.

Blockchain in satellite communications: scientific publications

The analysis of scientific publications in the field of blockchain in satellite comunication underscores a dynamic and rapidly evolving field, marked by intense research activity followed by signs of stabilization or shifts in focus. The global distribution of research output highlights not only the technological ambitions of leading nations, but also the strategic importance of blockchain technology in securing satellite communications on a worldwide scale. This global perspective is crucial for identifying potential areas for international collaboration and understanding geopolitical dynamics in technological development.

6 de La Beaujardiere, J., R. Mital and R. Mital (2019). Blockchain application within a multi-sensor satellite architecture. In IGARSS 2019-2019 IEEE International Geoscience and Remote Sensing Symposium, July. Institute of Electrical and Electronics Engineers, 5293–5296.

7 de La Beaujardiere, J., R. Mital and R. Mital (2019). Blockchain application within a multi-sensor satellite architecture. In IGARSS 2019-2019 IEEE International Geoscience and Remote Sensing Symposium, July. Institute of Electrical and Electronics Engineers, 5293–5296.

8 Wang, Y., Z. Su, J. Ni, N. Zhang and X. Shen (2021). Blockchain-empowered space-air-ground integrated networks: Opportunities, challenges, and solutions. IEEE Communications Surveys and Tutorials, 24(1), 160–09.

9 Ahmad, R. W., H. Hasan, I. Yaqoob, K. Salah, R. Jayaraman and M. Omar (2021). Blockchain for aerospace and defense: Opportunities and open research challenges. Computers and Industrial Engineering, 151, 106982.

10 Shang, B., Y. Yi and L. Liu (2021). Computing over space-air-ground integrated networks: Challenges and opportunities. IEEE Network, 35(4), 302–309.

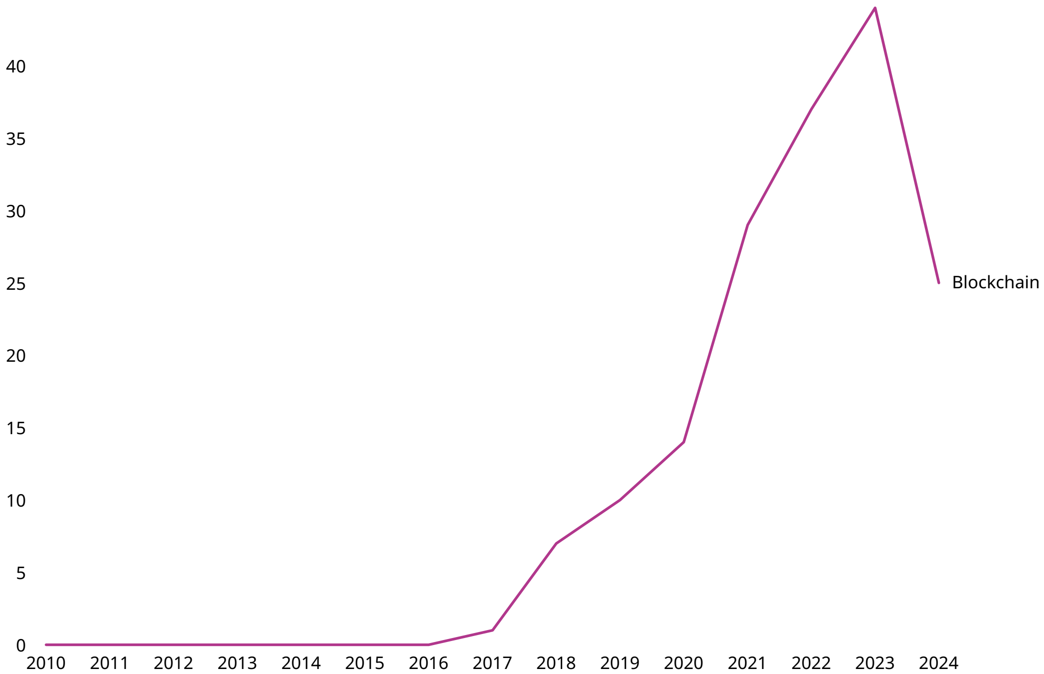
11 Alrubei, S. M., E. A. Ball, J. M. Rigelsford and C. A. Willis (2020). Latency and performance analyses of real-world wireless IoT-blockchain application. IEEE sensors journal, 20(13), 7372–7383.

12 Zhou, Q., H. Huang, Z. Zheng and J. Bian (2020). Solutions to scalability of blockchain: A survey. IEEE Access, 8, 16440–16455.

Figure D56 detailing the annual publication trends from 2017 to 2024 reveals a significant growth in research and publications up until 2023, followed by a notable decline in 2024. This trend suggests an initial period of heightened interest and activity in the field, likely driven by an increasing recognition of blockchain's potential to enhance the security and efficiency of satellite communications. The sharp increase in publications reflects ongoing development and exploration within the field, indicating a robust phase of innovation and theoretical exploration.

Annual publications from 2017 to 2023 show significant growth, but a notable decline occurred in 2024

Figure D56 Development of global scientific publications related to blockchain in satellite communications, 2017–2024

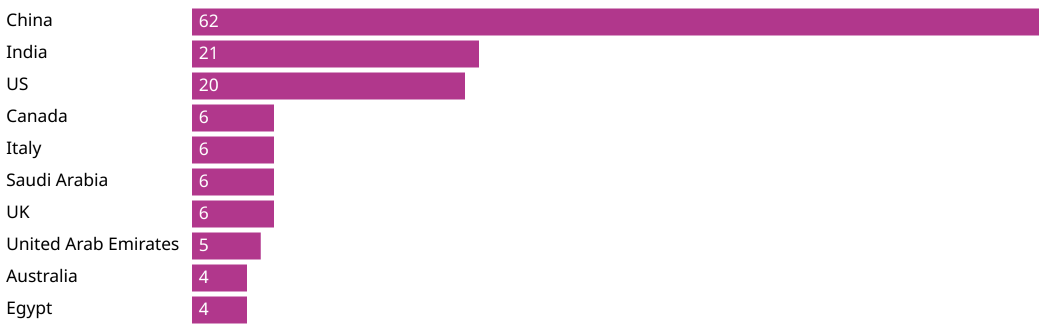


Source: WIPO, based on publication data from EconSight/Scopus, October 2024.

Figure D57 shows the geographical distribution of publications and emphasizes the global interest in blockchain applications for satellite communication, with significant contributions from a diverse set of countries. China leads in the number of publications, highlighting its strategic emphasis on space and communication technologies as part of its broader technological advancement goals.

China leads significantly in number of publications

Figure D57 Origin countries for scientific publications related to blockchain in satellite communications, 2000–2023



Source: WIPO, based on publication data from EconSight/Scopus, October 2024.

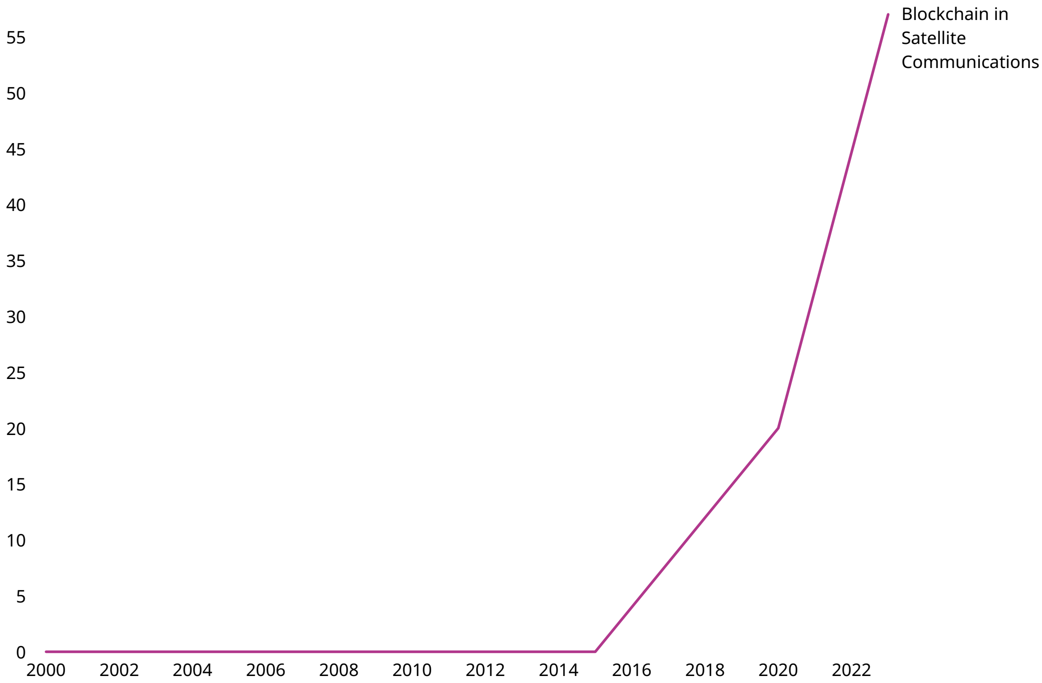
Other major contributors include India and the United States, indicating the existence of a strong research capability and interest in these countries as well. The participation of countries like Saudi Arabia and the United Arab Emirates reflects a growing interest in cutting-edge technologies within the Middle East, likely driven by recent initiatives aimed at economic diversification and technological independence.

Blockchain in satellite communications: patent data

Patenting activity in the field of blockchain in satellite communications only began to increase notably after 2017. In 2023, the number of published patent families reached 57 (Figure D58).

Patenting in blockchain for satellite communications significantly increased after 2017, reaching 57 patent families in 2023

Figure D58 Development of global patent family publications related to blockchain in satellite communications, 2000–2023

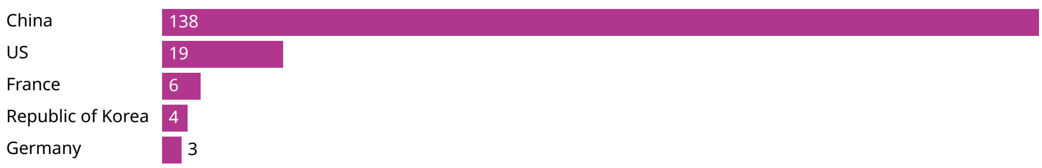


Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

China and the United States clearly dominate research activity related to the use of blockchain in satellite communications (Figure D59). China has published 138 patent families in this field since 2000, the United States ranks second with 19. France, in third place, has published only 6 patent families during the same period.

China clearly dominates patenting in blockchain for satellite communications

Figure D59 Patent family publications related to blockchain in satellite communications, 2000–2023



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2024.

Blockchain in satellite communications: patent example

In the early years of blockchain technology, Lockheed had already invented under EP3766190A1 a system for managing data storage on a satellite platform using blockchain technology. The core idea involves a network of satellites working together to maintain a blockchain ledger. When a first satellite identifies a request for a ledger entry in the blockchain, it distributes this entry to other satellites within the network, which act as full nodes for the blockchain. The receiving satellites verify the ledger entry and, if verified, they enter the ledger entry into their individual ledgers. If the entry is not verified, it is not recorded. This decentralized system ensures that multiple satellites participate in maintaining and verifying the blockchain, thus enhancing data integrity and reliability.

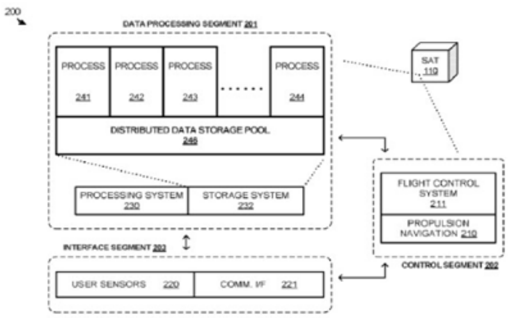


FIGURE 2

Source: EP3766190A1.

Additionally, the blockchain can be part of a distributed application running on multiple satellites, processing requests from ground systems, sensors or other satellites. Overall, the invention leverages blockchain technology to enhance the reliability and integrity of data storage and management across a network of satellites.

A patent from Lockheed describes a system in which satellites work together to maintain a blockchain ledger, by verifying and distributing ledger entries among themselves. A patent from China Mobil (CN117155458A) focuses on a low Earth orbit satellite internet of things (IoT) communication method that uses blockchain to securely collect, encrypt and transmit group data from ground-based IoT terminals to satellite consensus nodes, thus enhancing data transmission efficiency.

The invention relates to the field of communication and discloses a low Earth orbit (LEO) satellite IoT communication method and system based on blockchain technology and a storage medium. The method involves collecting terminal data from a group of terminals within the ground IoT system through a service node of the terminal group, resulting in group data. The terminal group, comprising service terminals and other terminals, is determined after grouping the ground IoT terminals. The service node is a service terminal registered to a space chain.

The collected group data is encrypted to produce encrypted data. These encrypted data are sent via the service node to a consensus node within the LEO satellite constellation in the satellite IoT system. These consensus nodes are consensus satellites registered to the space chain and are preset in various orbits of the constellation. This process aims to address the issue of low data transmission efficiency in LEO satellite IoT systems.

The method includes further steps to assure the proper transfer and verification of data. If no consensus node is within the visible range of the service node, the encrypted data are sent to a visible satellite node, which forwards it to a consensus satellite node in the same orbit. When a consensus node is within range, the data are sent directly to it. The consensus nodes verify the encrypted data and, upon validation, sign them to generate interactive data, which are sent to the system's control center.

Additional processes include the determination of service terminals, generation of service authentication keys and registration of service nodes to the space chain. The encrypted data are obtained by compressing the group data and encrypting them using the service node's public key, followed by signing with the private key. The system can detect abnormalities and remove malfunctioning nodes from the space chain. This blockchain-based communication method for LEO satellite IoT systems involves a combination of ground-based IoT and LEO satellite constellations, so as to enhance data transmission efficiency and reliability by leveraging blockchain technology for secure and verified data transactions.

Appendix

Methodology for patent analysis

Data collection, patent counting

- Simple published patent families are counted as a proxy for individual inventions in the report. A simple patent family is a set of patents in various countries in relation to a single invention. The technical content covered is considered to be identical. All patent documents have the same priority date or combination of priority dates. The first publication by a member of a patent family counts as the publication year.
- Most analysis in the report refers to numbers of patent families. Only published patent families have been studied.
- Patent families generally include only patents and not utility models, without assessing their legal status.
- The origin of the inventor (inventor's location or residence) is used as a proxy for the source of innovations. For patents with multiple inventors, we count the different locations listed and count the location for multiple inventors of the same origin once.

Utility models have been excluded from the patent analysis in this report, because the regional differences and lower inventive threshold for utility models can affect the accuracy and relevance of the analysis. [1] Utility models are not available in every country or region, therefore their inclusion can create inconsistencies in global studies, such as this report, for which comparability across countries and between regions is essential. The requirements for obtaining a utility model are also less stringent than those for a patent and they often cover incremental improvements rather than significant innovations, therefore including them can dilute the focus on more substantial technological advancements.

Patent indicators

Patent application

To obtain a patent, an application must be filed at the appropriate IP office together with all the necessary documents and fees. The IP office will conduct an examination to decide whether to grant or reject the application. Patent applications are generally published 18 months after the earliest priority date of the application. Prior to publication, the application remains confidential.

Patent classification

Patent classification is a system for examiners of IP offices or other people to code documents, such as published patent applications, according to the technical features of their content. The International Patent Classification (IPC) is agreed internationally. The European Patent Office (EPO) and United States Patent and Trademark Office (USPTO) launched a joint project to create

1 See, Utility models, available at: www.wipo.int/web/patents/topics/utility_models.

the Cooperative Patent Classification (CPC) in order to harmonize the patent classifications systems between the two offices.

Patent applicant/owner

Patents are filed by an applicant, which can be an organization or a natural person. Applicants are not inventors, even if sometimes they are similar. The applicant is in most jurisdictions and in most cases published with the patent and remains always the applicant. The applicant is not automatically the owner of a patent at a given time, even if that is often the case. Patents can be transferred or sold, or the applicant itself can be sold as a company in a merger or takeover. Therefore the “owner” of a patent might change over time and is not always published. For proper analysis, to consolidate incorrect spelling and to include merger and acquisition information in the analysis, the report used the ultimate owner concept in the IFI Claims global patent database. The most probable entity was then named as owner.

Patent family

A patent family is a collection of patent applications covering the same or similar technical content and all sharing one or more priority documents. Families are used to count inventions and not several patents corresponding to the same subject matter and filed in different jurisdictions. There are several definitions of patent families, including simple and extended patent families, depending on the number of priority documents shared (ranging from one to all priority documents). Patent family members are the individual patents filed in those jurisdictions where a patent applicant is seeking patent protection (e.g., WIPO, EPO) and all publications in relation to these. In the present study, we counted simple patent families (using a representative patent family member for each patent family), unless otherwise specified.

Granted patent

Once examined by the IP office, an application becomes a granted patent or is rejected. If granted, the patent gives his owner a temporary right for a limited time period (normally 20 years) to prevent unauthorized use of the technology outlined in the patent. Procedure for granting patents varies widely between locations according to national laws and international agreements. Note that in the same patent family, an application can be granted in one location and rejected in another.

Inventor country/location

The origin of the inventor (inventor’s location or residence) is used as a proxy for the source of innovation. For patents with multiple inventors, we counted the different locations listed and counted the location for multiple inventors of the same origin once. If no inventor address was available, the patent priority country/location was used as a proxy for the source of innovation.

Priority country/location

The first location in which a particular invention has a patent application filed, also known as the office of first filing.

Filing country/location

The filing country/location is the legal jurisdiction in which a member of a patent family filed a patent application to seek patent protection.

PCT (WO)

The Patent Cooperation Treaty (PCT) is an international patent law treaty concluded in 1970, administered by the World Intellectual Property Organization (WIPO), between more than 140 Paris Convention locations. The PCT makes it possible to seek patent protection for an invention simultaneously in each of a large number of locations by filing a single “international” patent application instead of filing several separate national or regional patent applications. The granting of patents remains under the control of the national or regional patent offices, which is referred to as the "national phase."

European patent (EP)

A European patent can be obtained for all the European Patent Convention (EPC) locations by filing a single application at the European Patent Office (EPO). European patents granted by the EPO have the same legal rights and are subject to the same conditions as national patents (granted by the national patent office). A granted European patent is a "bundle" of national patents, which must be validated at the national patent office to be effective in member locations. The validation process could include submission of a translation of the specification, payment of fees and other formalities at the national patent office. Once a European patent is granted, competence is transferred to the national patent offices. Other regional patents or procedures also exist: the Eurasian patent (EA), ARIPO patent (AP) for English-speaking Africa and OAPI patent (OA) for French-speaking Africa.

Relative Specialization Index

The Relative Specialization Index (RSI) compares the published patenting activity in two or more locations within the same technology area. RSI is a measure of a location's share of patent families in a particular field of technology as a fraction of that location's share of patent families in all fields of technology. It accounts for the fact that some locations file more patent applications than others in all fields of technology.

In other words, RSI has the advantage of providing a comparison of two locations' patenting activity in a technology relative to those locations' overall patenting activity. The effect of this is to highlight locations which have a greater specialism of the technology area studied than expected from their overall level of patenting, and which might otherwise appear further down in the top inventor location lists, often unnoticed. A positive RSI value indicates that a location has a higher specialization in this field than would be expected, whilst a negative value indicates a lower specialization than expected for that location.

The Relative Specialization Index (RSI) is calculated as follows:

$$RSI = \frac{X-1}{X+1}$$

where X is given by,

$$X_{c,t} = \frac{n_{c,t}/N_c}{N_t/N}$$

and

$n_{c,t}$ is the number of published patent families in country c for technology t,

$N_c = \sum_t n_{c,t}$ is the number of published patent families in country c in all technologies,

$N_t = \sum_c n_{c,t}$ is the number of published patent families in technology t in all countries, and

$N = \sum_c \sum_t n_{c,t}$ is the number of published patent families in all technologies and all countries.

Patent searches

Full details of the patent search strategies used to define the technology areas analyzed in this report can be accessed and downloaded from the WIPO Technology Trends webpages. [2]

2 See, WIPO technology trends, available at: www.wipo.int/web/technology-trends.

This technical annex to the *WIPO Technology Trends* Report on the Future of Transportation explores the rapidly advancing field of space transportation.

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