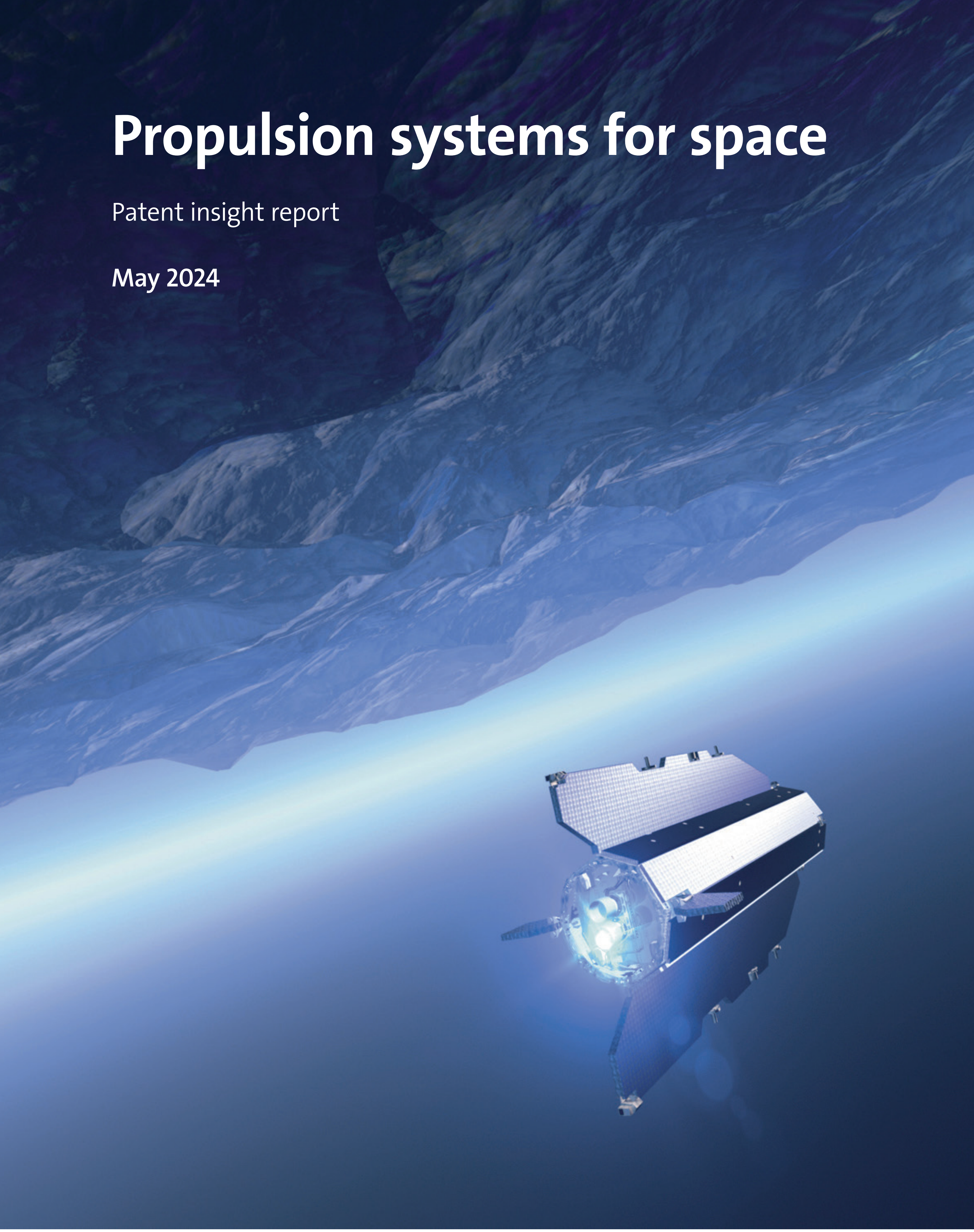
Propulsion systems for space

Patent insight report

May 2024



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Executive Summary

Propulsion is a key element in all space activities because it provides the fundamental function of producing thrust to move launchers, satellites, and other assets from Earth to space or within space.

Space propulsion encompasses different principles, most prominently chemical and electric propulsion concepts as well as alternative and emerging concepts accompanied by a variety of propellants and even “fuel-less” concepts, such as solar sails.

The significance of propulsion capabilities stems from their transversal **enabling role for a spectrum of applications**, including access to space; collision avoidance; on-orbit servicing, assembly, manufacturing and space exploration.

For this study a total number of 4559 patent families filed at 52 patent authorities have been identified with applicants registered in 43 countries and inventors residing in 53 countries. The data set comprises 1178 international patent families (IPF) in four distinct technology principles, namely chemical propulsion, electrical propulsion, “alternative” propulsion and propellants.

Figure E1

National filings vs International Patent Family (IPF) by country

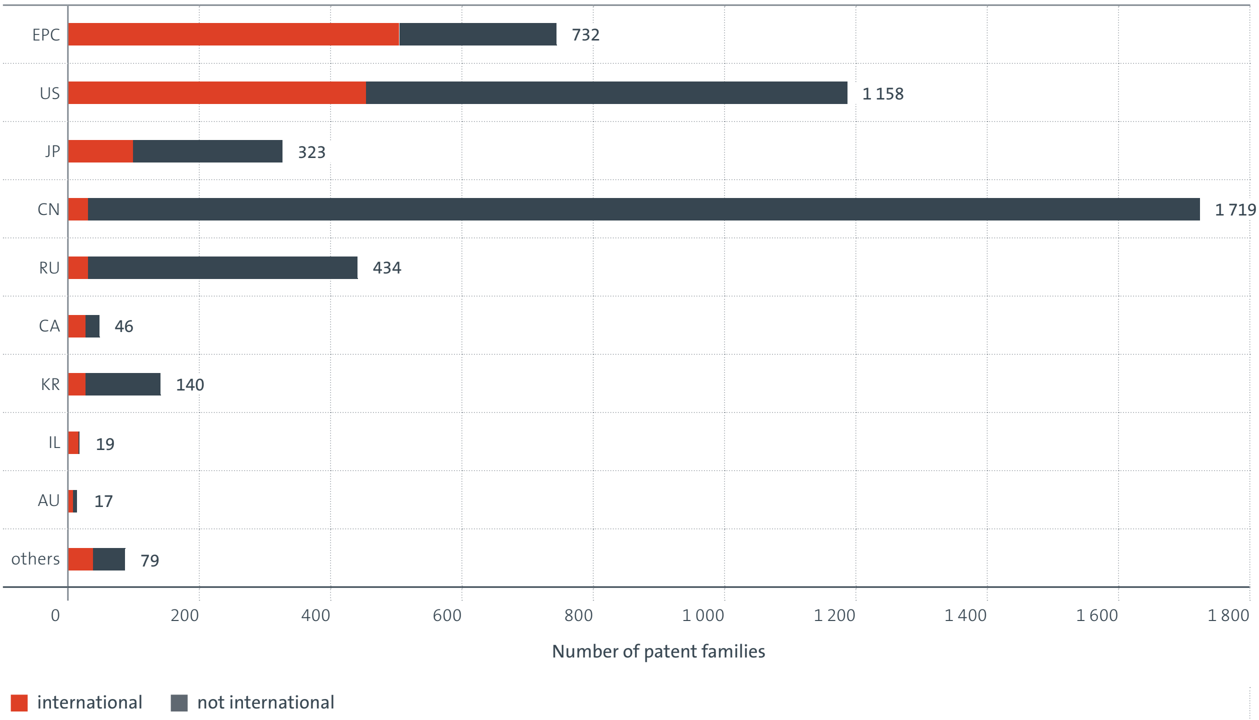
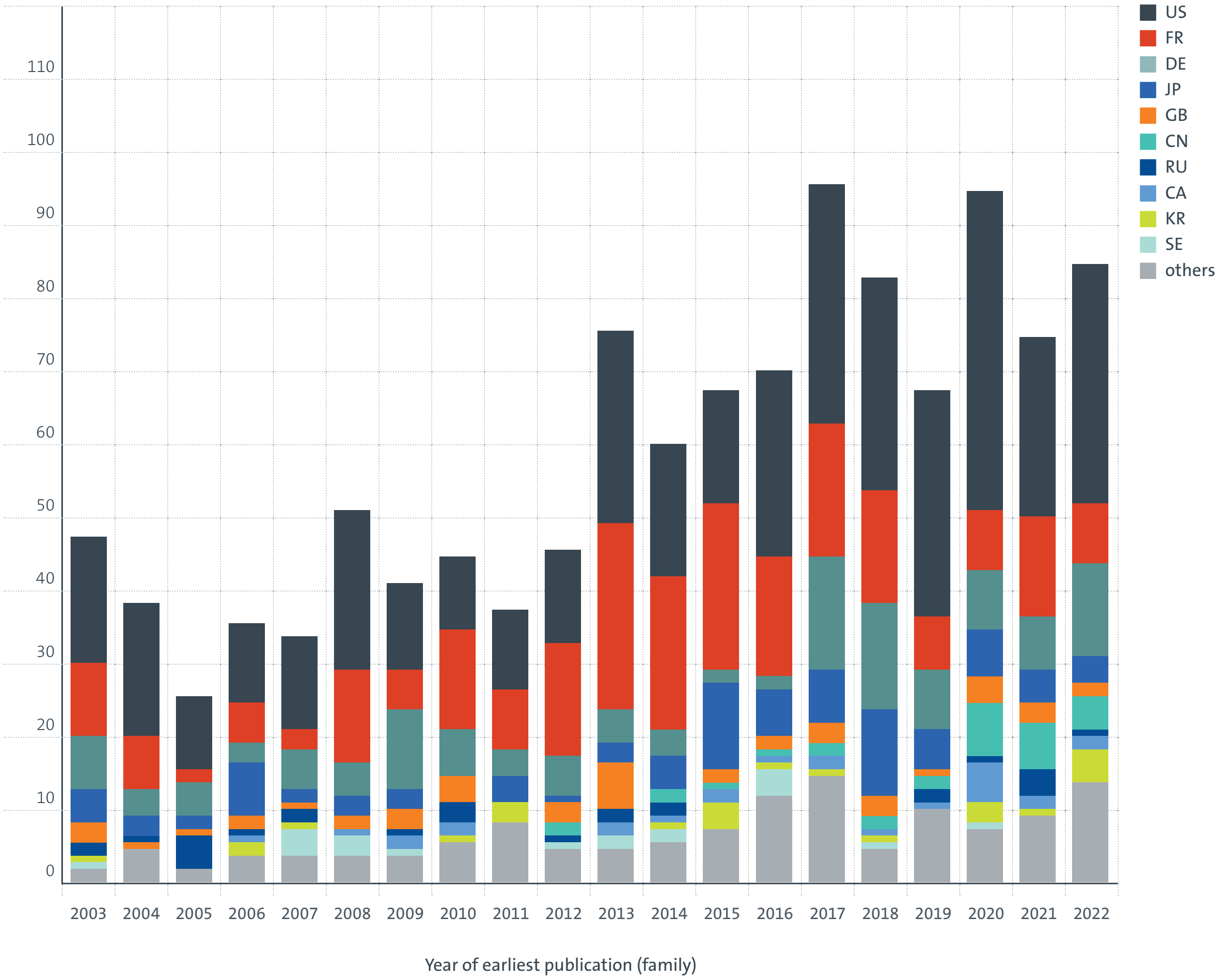


Figure E2

International patent families by applicant country



An analysis of patent data for space propulsion systems has revealed the following key takeaways:

1. **Globally, there is a notable growth in patent filing activity.** Space propulsion systems have witnessed a strong increase in patent activity over the last 20 years (especially since 2011) – averaging out at 9% annually.

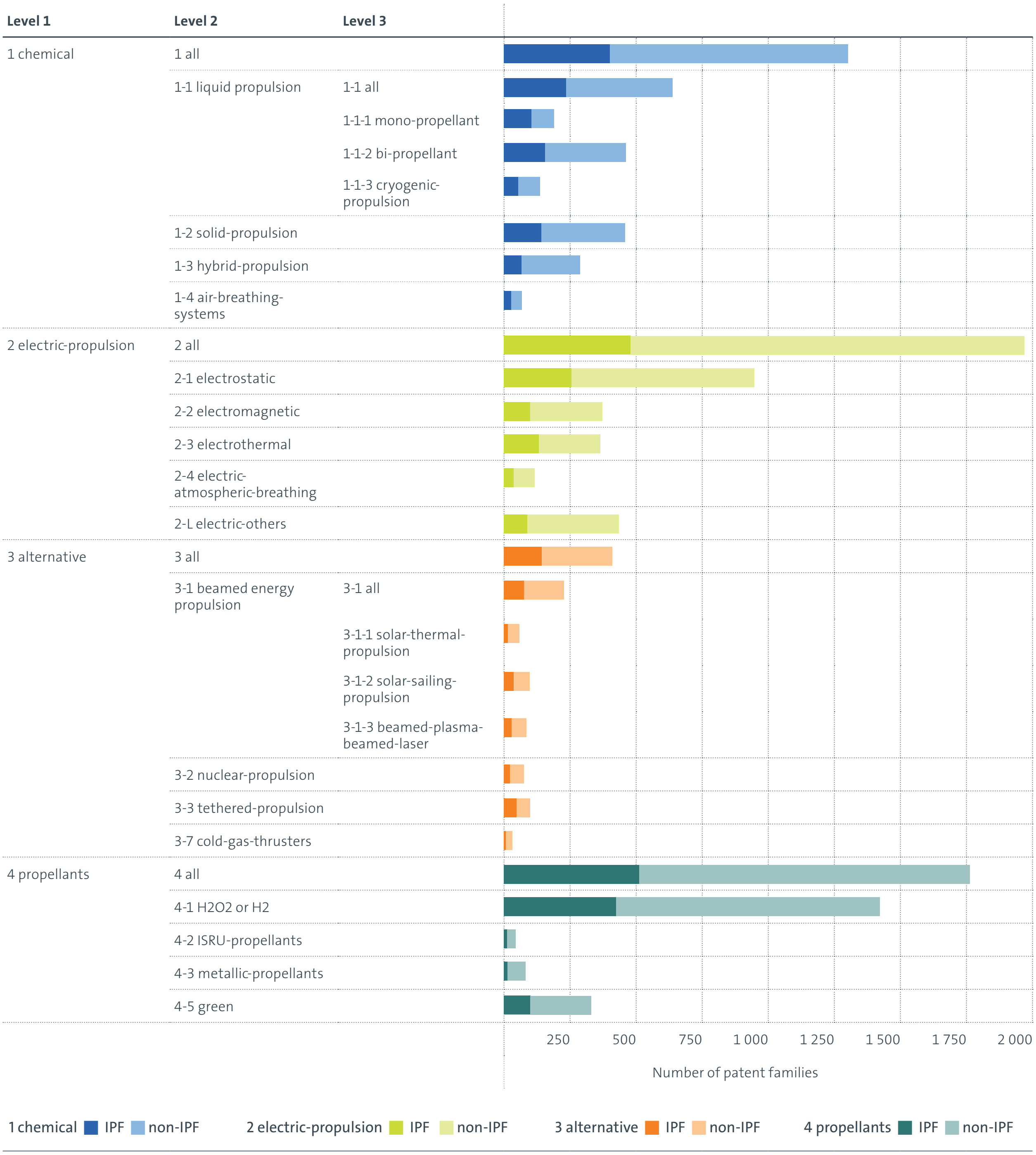
2. **International patent activity is primarily concentrated among the players who have traditionally dominated the space sector.** This encompasses applicants from the US, Japan, Europe (primarily France and Germany), China and Russia.

3. **International filing activity of European applicants is high (37%) but following a slowing trend line.** There is an absolute and relative slowdown of propulsion system development in Europe, in line with the continent's stagnant position in other, especially high-tech, sectors. Despite Europe's efforts to be at the forefront of climate protection and green policies through the EUs Green Deal, the number of patent families about green propellants originating from the continent is of marginal significance.

4. **Electric Propulsion is on the rise.** Electric propulsion has seen the largest increase in patent filings over the last 20 years, especially in China, and has surpassed chemical propulsion in recent years.

Figure E3

Technology map



1. Space propulsion

1.1. Introduction to the propulsion market

The current momentum within the global space sector is unprecedented. In 2022, there were over 1 000 companies active in the market, which is twice the equivalent number of 2012.[1] There is a notable movement towards commercialisation, making space a pivotal sector with substantial future benefits and potential. The number of satellite launches has seen a remarkable increase, rising from an average of 300 per year between 2010 and 2019 to over 2 800 in 2023[2].

One of the key characteristics of the space domain in recent years has been the increasing role of private players, with SpaceX as the most prominent example. Despite experiencing significant growth, private investments in space still constitute a small fraction of public space funding. Institutional spending in 2022 almost reached EUR 100bn[3] and the growing interest from commercial entities has also sparked a surge in private sector involvement. Private capital is now playing a crucial role, amounting to over EUR 8.8bn in 2022[4].

Propulsion is a key element in all space activities because it provides the fundamental function of producing thrust to move launchers, satellites, and other assets from Earth to space or within space. Space propulsion systems are fundamental for accessing space, enabling orbit acquisition, orbit changes, orbit maintenance, position control, station-keeping, attitude control, proximity operations, collision avoidance, disposal at end of life and deep-space manoeuvres including landing and ascent. As a result of the emerging demand for the various use cases of propulsion, as well as the recent technological developments, companies working in the propulsion domain have recently received significant funding on a worldwide scale. According to independent assessments[5][6][7][8], the space propulsion market segment was estimated to amount to around EUR 9.2bn in 2022 and is projected to double or even triple in value by around 2030, with the main markets being North America, Europe and Asia-Pacific. The main drivers are the overall growth in the space economy, driven by an increased demand for space applications (combating climate change, security, meteorology, connectivity) and the development of reusable launch vehicles.

1.2. Propulsion as a key enabler

The importance of propulsion capabilities stems from their transversal enabling role in the space sector for a spectrum of applications. This concerns not only access to space through launch vehicles but also the evolving focus on sustainability, the emerging space logistics and on-orbit servicing, assembly and manufacturing (OSAM) market for the low Earth orbit (LEO) economy, and renewed exploration ambitions for the moon and beyond.

Access to space: Propulsion is crucial for accessing space and to reap the benefits of telecommunication, navigation, and Earth observation. Today, the launch sector is subject to multiple trends. First and foremost, the launch cadence is increasing every year, driven by a growing demand for services enabled by space infrastructure. This trend drastically intensified with the emergence of LEO satcom constellations such as Starlink or OneWeb and Amazon Kuiper as well as the two planned Chinese institutional constellations Guowang and G60. The second major breakthrough is vertical landing and the reusability of the booster stage of launch vehicles as pioneered by SpaceX's Falcon 9. Even though Falcon 9 is currently the only launcher with operational and reliable technology for booster stage reusability, reusable rocket launches accounted for 41% of all launches in 2023[9]. The third major trend concerns the transformation to a carbon neutral and sustainable

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[1] Market analysis conducted by Boston Consulting Group (BCG) and ESPI

[2] ESPI launch database (2024)

[3] SIA/Bryce 2022 https://brycetech.com/reports/report-documents/SIA_SSIR_2022.pdf

[4] ESPI Space Venture Europe 2022

[5] https://www.marketsandmarkets.com/Market-Reports/space-propulsion-market-118742255.html

[6] Fortune Business Insights 2022 https://www.fortunebusinessinsights.com/space-propulsion-systems-market-105870

[7] Polaris Market Research 2021 https://www.polarismarketresearch.com/industry-analysis/space-propulsion-market

[8] Allied Market Research 2022 https://www.alliedmarketresearch.com/space-propulsion-system-market-A10443

[9] ESPI launch database 2024

economy; this means that the launch sector is faced by its environmental footprint with efforts being made to mitigate its pollution by developing green and non-toxic propellants. Furthermore, geopolitical instabilities have underlined the importance of sovereignty and critical capabilities. Independent access to space has emerged as a major topic in Europe, fuelling the development of launch vehicles throughout the continent.

Collision avoidance: The crowding of Earth orbits with growing numbers of spacecraft and amounts of space debris is posing an increasing threat to operational space systems, including crewed spacecraft and stations. The increased interest in the development of new LEO-based services, such as large constellations of communication satellites, led to a significant increase in the number of orbiting objects and therefore a higher likelihood of collisions, reducing operational safety and long-term sustainability. Looking ahead, one major way of mitigating space debris will be through greater manoeuvrability of spacecraft, achieved, for example, by increasingly equipping satellites with on-orbit propulsion systems to effectively modify their orbits when needed. Public and private players in the space sector have recognised this threat and started to develop measures to prevent their spacecraft from being hit by debris and also to prevent satellites becoming debris in the future. A combination of technical developments and regulatory advancements is facilitating an effective global Space Traffic Management (STM) system[10] and spacecraft propulsion can be considered as an important building block in this vision.

On-orbit servicing, assembly, and manufacturing (OSAM): OSAM refers to services performed on orbiting spacecraft by servicing vehicles. Here, in-space propulsion enables last-mile delivery, inspection, repair, de-orbiting, refuelling, recharging, relocation, station-keeping, reconfiguration and assembly. OSAM is expected to become an essential part of the future LEO economy, with assessments of future market values varying between EUR 2.8bn and EUR 11bn, depending on the definition and scope of OSAM. In the long term, such services could also foster ambitious space markets, such as space-based solar power or data centres in space[11]. While this segment is still in a rather early development stage, various successful demonstrations and test cases and increasing public policy interest are paving the way towards OSAM becoming an integral component of the future space economy.

Exploration: Innovation in propulsion systems could also enable more ambitious long-term and deep space exploration in the future. This includes travel to unexplored destinations in the solar system and surface landings on other celestial bodies. Furthermore, more advanced propulsion techniques such as solar sails[12] or nuclear propulsion[13] could be used to increase the feasibility of exploring Mars and the planets and moons beyond it. Notably, growing interest in nuclear propulsion concepts for spacecraft has been reflected in public policies – in the United States, the country that currently has the most developed space exploration capabilities, nuclear propulsion is a salient topic, with governmental initiatives put in place in recent years in order to facilitate technology development that will enable future exploration ambitions [14,15]. The continuous interest of governments in utilising nuclear energy sources for spacecraft power and propulsion since this was first considered feasible means that nuclear propulsion is also a matter of diplomatic significance. The UN Committee on the Peaceful Uses of Outer Space (COPUOS) has for a long time provided a platform for international dialogue about this topic, and jointly it developed the Safety Framework for Nuclear Power Source Applications in Outer Space in 2009 in conjunction with the International Atomic Energy Agency (IAEA).

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[10] According to the European Union “STM encompasses the means and the rules to access, conduct activities in, and return from outer space safely, sustainably, and securely”

[11] An in-depths analysis on State of Play and Perspectives on Future Evolutions in OSAM can be found in the ESPI Report 87 on On-orbit Servicing, Assembly, and Manufacturing. https://www.espi.or.at/wp-content/uploads/2023/10/Final-Report-OSAM-1.pdf

[12] https://www.nasa.gov/news-release/nasa-supported-solar-sail-could-take-science-to-new-heights/

[13] https://www.nasa.gov/tdm/space-nuclear-propulsion/#:~:text=Space%20nuclear%20propulsion%20is%20a,propulsion%20systems%20%E2%80%93%20thermal%20and%20electric.

[14] https://trumpwhitehouse.archives.gov/presidential-actions/memorandum-national-strategy-space-nuclear-power-propulsion-space-policy-directive-6/

[15] https://trumpwhitehouse.archives.gov/presidential-actions/executive-order-promoting-small-modular-reactors-national-defense-space-exploration/

1.3. Space propulsion systems

The majority of the use cases for space propulsion are covered by the following propulsion principles, which also represent the main subject matter covered in this patent insight report:

1.3.1. Chemical propulsion

Chemical propulsion for space applications covers a wide range of propulsion system concepts and components that are based on the use of chemical energy. A broad overview of the different concepts is given in the table below:

Table 1

Overview chemical propulsion principle[16]

<table>
<tr><th colspan="3">Chemical propulsion</th></tr>
<tr><td colspan="2">Liquid propulsion</td><td rowspan="2">Solid propulsion</td></tr>
<tr><td>Monopropellants</td><td>Bipropellants</td></tr>
<tr><td colspan="3">Hybrid propulsion</td></tr>
</table>

Chemical propulsion concepts are relevant for the following major applications:

- reusable or expendable launch vehicles/upper stage/space tugs propulsion;
- spacecraft on-board propulsion (including micro-propulsion);
- re-entry manoeuvring propulsion sub-concepts.[17]

In practice, the liquid propulsion concept is divided into the sub-concepts monopropellants, where a single propellant liquid is used, or bipropellants, with one liquid acting as fuel and the other as oxidiser.

Solid propulsion concepts typically utilise a solid self-burning mixture of fuel and oxidiser and are prominently used in booster or main stages of launcher systems. The hybrid propulsion concept typically uses a solid fuel and a liquid or gaseous oxidiser, but is currently limited to suborbital applications, such as sounding rockets.

Figure 1

VEGA C artist's impression Photo: ©ESA, J. Huart[18]

The Vega-C is based on the Vega launch vehicle and serves as an example of combined solid and liquid propulsion. As with the Vega, its main elements consist of three solid fuel stages, while an upper fourth stage is powered by a re-ignitable liquid engine and a payload fairing.[19]

Classic fuels and oxidisers for chemical propulsion are liquid hydrogen (LH2) and liquid oxygen (LOX), hydrazine (N2H4), monomethyl hydrazine (MMH). In the past, unsymmetrical dimethyl hydrazine (UDMH), dinitrogen tetroxide (N2O4), hydrogen peroxide (H2O2) and nitric acid (HNO3) were also used. This is a non-exhaustive list, many other combinations and variations exist.

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[16] Table adapted from: NASA Glenn Research Center, Chemical Propulsion Systems https://www1.grc.nasa.gov/research-and-engineering/chemical-propulsion-systems/

[17] ESA Technology Tree Version 4.1, https://esamultimedia.esa.int/multimedia/publications/STM-277/STM-277.pdf

[18] https://www.esa.int/ESA_Multimedia/Images/2022/06/Vega-C_VV21_LARES-2_livery_artists_impression

[19] https://www.esa.int/Enabling_Support/Space_Transportation/Launch_vehicles/Vega-C

Figure 2

Orion crew capsule with ESA's service module, artist's impression, Photo: ©ESA, D. Ducros[20]

The European Service Module for the Orion crew capsule utilises three different engine types with thrust outputs between 200 N and 25.7 kN, which are fuelled by oxides of nitrogen (MON) and MMH.

1.3.2. Electric propulsion

The electric propulsion principle uses electrical energy to accelerate a propellant. The working mechanism comprises three main concepts, namely electrothermal, electrostatic and electromagnetic. Within the electric propulsion categories multiple types for electric propulsion thrusters exist as shown in the table below.

Due to their typically high specific impulse, electric propulsion systems can be utilised advantageously in the following applications:

- spacecraft on-board propulsion (including micro-propulsion);
- orbital stages/tugs propulsion
- missions with a long travel distance that allow for an extended phase of acceleration.[22]

Examples of propellants used in such concepts are krypton (Kr), argon (Ar) and xenon (Xe).

Table 2

Overview of electric propulsion concepts[21]

	Electrothermal	**Electrostatic**		**Electromagnetic**
Concepts	Gas heated by a resistance or by arc discharge and then expanded through nozzle	Ions electrostatically accelerated		Plasma accelerated via interaction of electric and magnetic fields
Types	– Resistojet – Arcjet – Microwave Electrothermal Thrusters (MET)	– Electrospray – Gridded Ion Engines (GIE) – Field Emission Electric Propulsion (FEEP)	Plasma Thrusters	
			– Hall Effect Thruster (HET) – High Efficiency Multistage Plasma Thruster (HEMPT) – Quad Confinement Thruster (QCT)	– Magneto Plasma Dynamic Thruster (MPD) – Pulsed Plasma Thruster (PPT) – Helicon Plasma Thruster (HPT) – Vacuum Arc Thruster (VAT)

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[20] https://www.esa.int/ESA_Multimedia/Images/2015/11/Orion_ESM2

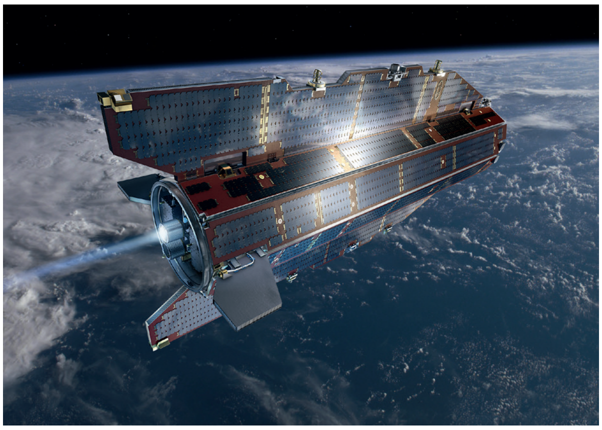
[21] Table adapted from: European Space Harmonisation Dossier - Electric Propulsion Technologies (Version 4.2 2023, full access for eligible participants can be requested via https://technology.esa.int/page/harmonisation)

[22] ibid

Lastly, Atmospheric-Breathing Electric Propulsion (ABEP) systems use atmospheric gases as propellant, enabling extended satellite operations in Very Low Earth Orbit (VLEO, 160-250 km) without using on-board propellant. ABEP in VLEO enables low latency time, high resolution for optical payloads, and frequent revisits. As mentioned, a remarkable satellite using a gridded ion engine is GOCE (Gravity field and Ocean Circulation Explorer), which was launched on 17 March 2009. The sleek aerodynamic design immediately sets it apart from most other satellites, as apparent from figure 3.

Figure 3

GOCE satellite in orbit, artist's impression ©ESA, AOES Medialab[23]



The system uses electrically charged xenon to create a gentle thrust. The system continually generates tiny forces between 1 and 22 millinewtons (mN), depending on how much drag the satellite experiences as it orbits Earth. The satellite's sophisticated electric propulsion system has shown that it is possible to completely compensate for any drag effects, thus enabling unprecedented accuracy in measuring the Earth's gravitational field.

1.3.3. Alternative space propulsion

Beamed energy propulsion

The beamed energy propulsion concept covers a variety of sub-concepts that have been proposed over the past few decades. In particular, it refers to propulsion sub-concepts such as sails, where propulsion is provided by the radiation pressure of the sun or a laser.

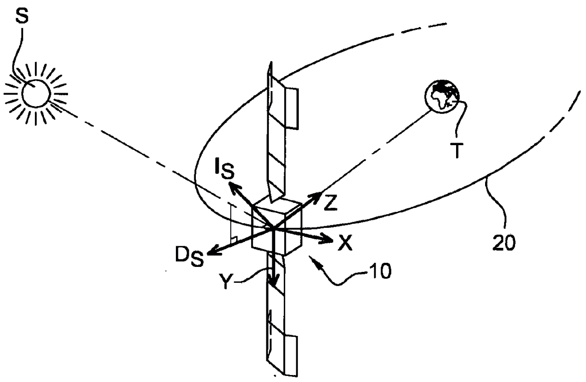
Water propulsion

Water propulsion systems are currently being developed for various applications. In the search for non-toxic, non-carcinogenic and generally non-hazardous replacements for hydrazine, water is the ultimate green propellant. Several different types of water propulsion exist, with possibly the most common current application being a Water-Resistojet (WR). This type of electrothermal electric propulsion uses the water itself as propellant. In contrast, Water Electrolysis Propulsion (WEP) employs an electrolyser to generate oxygen and hydrogen gases from the stored water. The two gases are then used to operate conventional chemical propulsion thrusters or Hall Effect Thrusters (HET). Therefore, water propulsion systems cannot be defined as strictly electric or chemical propulsion systems.

Figure 4 illustrates such an invention. The respective patent describes the exploitation of solar pressure, in particular proposing a device for controlling the attitude of a satellite, which makes it possible to control the attitude of the satellite along three independent axes without requiring the solar generators to be re-aligned relative to the Sun.

Figure 4

EP2643215B1[24]



Furthermore, concepts of a heat exchanger heated by beamed energy or mirror systems that focus the energy on a focal point are also discussed in this propulsion domain. Such concepts transfer the energy to an on-board propellant which can be ejected to propel the spacecraft.

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[23] https://www.esa.int/Applications/Observing_the_Earth/FutureEO/GOCE/Introducing_GOCE

[24] https://worldwide.espacenet.com/patent/search/family/045509523/publication/EP2643215B1?q=pn%3DEP2643215B1

Tethered propulsion

Concepts and techniques related to the use of long cables to create a force at the end-masses of the system due to centrifugal force, e.g. inert tethers. Electrodynamic tethers utilise the electromagnetic interaction between a current flowing through the tether and the planet magnetosphere. Lastly, electrostatic tethers are driven by a constant electrostatic field that exchanges momentum and energy with charged particles, e.g. a planets ionosphere[25].

Nuclear propulsion

Nuclear propulsion concepts and techniques relate to the use of nuclear engines to produce thrust. The main working principles of interest for space are classified as nuclear thermal concepts that use a working fluid that is heated to a high temperature inside a nuclear reactor, or nuclear electric concepts, that use the thermal energy from a nuclear reactor converted into electrical energy to drive an electrical thruster. Their high efficiency when compared to chemical concepts is of interest for deep space science missions and (crewed) exploration missions.[26]

1.3.4. Technology developments

In view of the strategic importance of space activities and the growing economic interest in them, new capabilities in space propulsion are actively being sought. In Europe, the ESA has identified multiple pathways to facilitate European access to space, and new mission profiles. These include developments suitable for new applications that comply with new requirements, such as non-toxic propulsion, very high thrust sub-concepts, throttle-ability, reusability, components for refuelling and space debris mitigation. A further overarching priority is reducing development times and costs while enhancing the competitiveness of European propulsion products and processes, especially targeting the industrialisation of electric propulsion concepts.[27]

Where space transportation technologies are concerned, the European strategy targets developments towards reusability, intelligent hardware, increased autonomy and software-driven design. Emerging space services and applications such as spacecraft tugging, in-orbit assembly, life-extension and active debris mitigation are also being investigated, including developments for hypersonic suborbital and orbital flight capabilities. Where existing products are concerned, the targets are improved modularity and assembly, and a reduction in the costs of system developments.[28]

Dual-mode sub-concepts (switching between bipropellant and monopropellant propulsion modes) are of interest for current and future missions using chemical propulsion. Their flexible performance and a potential simplification of satellite systems could lead to increased payloads and cheaper propulsion systems. In addition, one prospective application is hybrid propulsion (usually solid fuel combined with a liquid oxidiser) to substitute hydrazine-based sub-concepts. However, first the hybrid motor performances need to be increased until they match the required performance in respect of bipropellant sub-concepts.

The continuing industrial trend towards micro- and nanosatellites (e.g. Cubesats) increases the need for Cubesat propulsion (chemical or electric) and low power electric propulsion. The capability to build such systems already exists in Europe where Cubesat propulsion technologies are concerned, key areas of development have been identified by the European Space Agency, including the miniaturisation of propellant storage and feeding systems, as well as high-voltage electronics for applicable electric propulsion concepts. Development activities are also aimed at complete miniaturised propulsion systems.[29] In addition, the dependence on micro-manufacturing techniques, the scalability and control of manufacturing processes and the need to manage heat dissipation are particular challenges in the development of Cubesat propulsion.

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[25] ESA Technology Tree Version 4.1, https://esamultimedia.esa.int/multimedia/publications/STM-277/STM-277.pdf

[26] ibid

[27] ESA's Technology Strategy (Version 1.2, September 2022), https://esamultimedia.esa.int/docs/technology/ESA_Technology_Strategy_Version_1_0.pdf

[28] ibid

[29] https://www.esa.int/ESA_Multimedia/Images/2023/09/Mini_space_thruster_that_runs_on_water

Moreover, measures for space debris mitigation, particularly for low Earth orbits (LEO), introduce a need for rapid de-orbiting of satellites after their mission ends. To fulfil the stringent requirements set or adapted by entities such as ESA[30] and the Federal Communications Commission (US)[31], reliable low power electric propulsion is expected to become a crucial factor for such satellite missions.

Lastly, ongoing developments in electric propulsion target several capabilities for increasing the maturity and availability of systems and components in Europe. Notably, these include:

- Maturing and qualifying high-power systems (> 20 kW) for deep space exploration and, e.g., cargo transportation to future destinations such as the Moon and Mars.
- Maturing and qualifying of 5 - 7 kW Hall effect thrusters and gridded ion engines (GIE) for telecommunication, navigation, space transportation and exploration applications.
- Maturing and qualifying low-cost systems for < 1 kW range for LEO constellations.
- Maturing and qualifying low-cost systems for < 300 W range for, e.g., commercial small satellites and science missions.
- reduce dependence in supply chain and establish dual source strategies for critical technologies

1.4. The study

By virtue of their respective missions and activities, the EPO, ESPI and ESA share a common interest in the study of patent filing statistics to better understand technological trends in the space sector. In 2020, 2021, and 2022 the EPO and ESPI, in collaboration with ESA, published three patent insight reports:

1. The first report (July 2021) examined patent filing statistics over the past 30 years in cosmonautics to assess the relevance of that data to the identification of trends in the space sector.[32]
2. The second report (November 2021) addressed the evolution of patent filing activity in space applications of quantum technologies.[33]
3. The third report (October 2022) deals with the patent landscape and emerging trends in green applications of space borne sensing.[34]

Building on that partnership, the present study, launched in 2023, focuses on assessing patent filing statistics in the propulsion domain.[35] To do so, the study has used various resources, including EPO patent databases and registers, ESPI publications, ESA technical expertise and other available public reports and scientific articles.

EPO: The European Patent Office examines European patent applications, enabling inventors, researchers and companies from around the world to obtain protection for their inventions in up to 44 countries. The EPO is the executive arm of the European Patent Organisation, an international organisation with 39 member states. The EPO's activities and budget are overseen by the Organisation's Administrative Council, which consists of representatives of the member states.

ESPI: The European Space Policy Institute is Europe's independent think-tank for space. Based in Vienna, Austria – the world's capital of space diplomacy, and working in a non-profit capacity, ESPI promotes European space policy on a global level; facilitates an active forum for the analysis and discussion of European needs, capabilities, and long-term prospects in space activities; and makes proposals and recommendations to European decision-makers and institutions.

ESA: The European Space Agency is an international organisation with 22 member states. It is Europe's gateway to space. Its mission is to shape the development of Europe's space capability and ensure that investment in space continues to deliver benefits to the citizens of Europe and the world. By coordinating the financial and intellectual resources of its members, it can undertake programmes and activities far beyond the scope of any single European country.

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[30] ESA Space Debris Mitigation Requirements, https://technology.esa.int/upload/media/ESA-Space-Debris-Mitigation-Requirements-ESSB-ST-U-007-Issue1.pdf

[31] FCC ADOPTS NEW '5-YEAR RULE' FOR DEORBITING SATELLITES TO ADDRESS GROWING RISK OF ORBITAL DEBRIS, https://docs.fcc.gov/public/attachments/DOC-387720A1.pdf

[32] https://www.espi.or.at/wp-content/uploads/2022/06/EPO-ESPI-Report-Cosmonautics-The-development-of-space-related-technologies-in-terms-of-patent-activity.pdf

[33] https://www.espi.or.at/wp-content/uploads/2021/11/Quantum-Technologies-and-Space-Collaborative-Study.pdf

[34] https://link.epo.org/web/Space-borne%20sensing%20and%20green%20applications%20report.pdf

[35] https://worldwide.espacenet.com/patent/static/cpc.html#!/CPC=B64G1/40

1.5. Using patent information

Patents are exclusive rights that can only be granted for inventions in any field of technology, provided they are novel, inventive and industrially applicable. High-quality patents are assets that can help attract investment, secure licensing deals and provide market exclusivity. Patent owners pay annual fees to maintain patents that are of commercial value to them and protect their inventions from being openly used by others, including competitors, in all protected markets. A patent can be maintained for a maximum of 20 years. In exchange for these exclusive rights, all patent applications are published, revealing the technical details of the inventions in them.

Therefore, patent databases contain a wealth of technical information on both patent applications and granted patents, much of which cannot be found in any other source and which anyone can use for their own research purposes. The EPO's free Espacenet database contains more than 150 million documents from over 100 countries and comes with a machine translation tool in 32 languages. Patent filing statistics provide interesting indicators to measure and examine innovation, commercialisation and knowledge transfer trends. The protection of intellectual property is very well documented in national and international databases and registers, which track bibliographic and legal event data on patent applications. Detailed information on the data coverage of worldwide patent data distributed by the EPO can be found here[36]. For some countries (e.g. India) data is missing.

Dedicated exploitation of these patent databases and registers can reveal new insights into sector trends and support informed decision-making processes. Patents provide means of observing technology trends, key innovators and policies in various jurisdictions. For this purpose, patent searches are useful in identifying patent documents related to specific technologies. The result sets of these searches are generally appropriate for statistical analyses on patent aggregates such as company portfolios or comparisons between countries. Statistical analyses are not recommended for the assessment of single, specific patents.

This information can be combined with further public information such as national R&D budgets and specific market studies.

1.6. Methodology

The information, data and analysis provided in this study are primarily based on dedicated exploitations of EPO patent databases (e.g. PATSTAT[37]) and registers covering relevant patent publications between 2003 and 2022. The EPO was responsible for creating the domain-specific queries and the structured dataset for the analysis, with assistance from several ESA experts in identifying relevant technologies.

The search queries were developed and validated in the examiner tool ANSERA and are included as supplementary information (data) with the publication of this report.

Figure 5

High Level Methodology

Prepare

Investigate possible material of interest

- Relevant technology dossiers
- ESA Competence Domains
- ESA Technology Domains
- Applicable Industry Reports
- Policy Landscape
- Expert consulting to confirm relevant information
- Create a shortlist of material, technology, applications, etc.

Collect

Identify and collect all relevant patent documents in the selected domain

- Split search queries for each topic
- Develop individual search queries with balance between precision and recall

Filter

Apply additional filters to identify

- Country of applicants
- International patent families
- Top applicants
- Co-applicants
- Forward citations
- Granted patents

Insight

Formulate insight and intelligence

- Visualise dataset and trends
- Identify connections, correlations and networks
- Use further combinations of indicators to investigate the dataset in-depth

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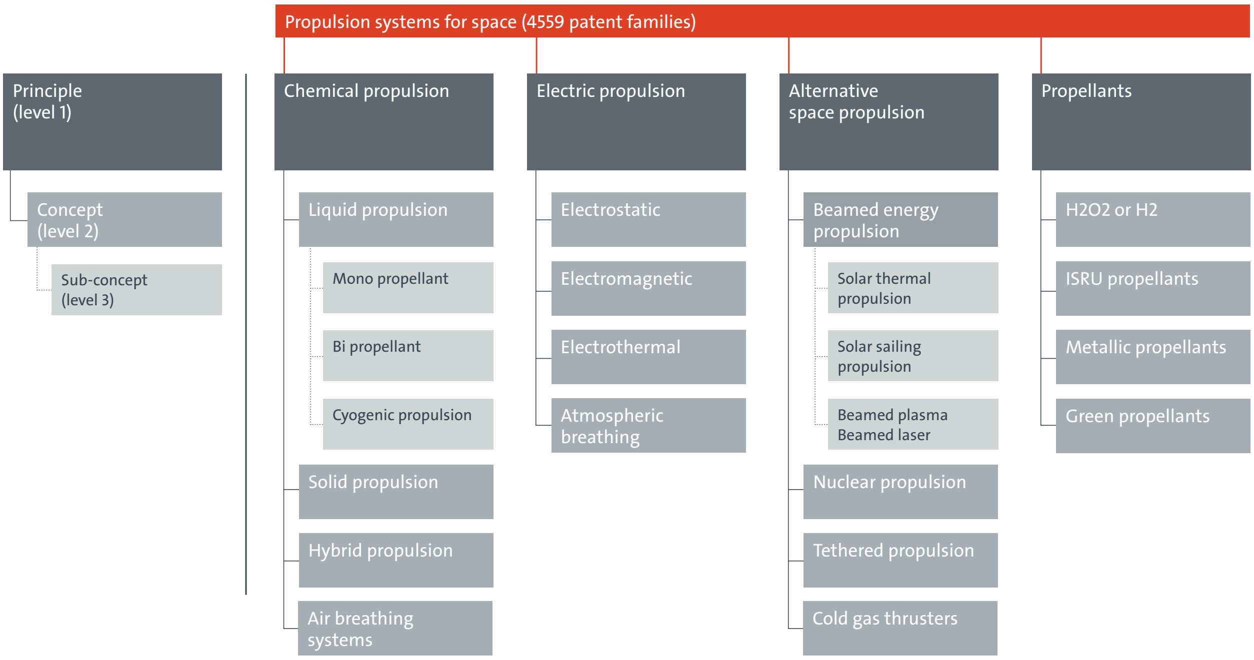
[36] https://www.epo.org/en/searching-for-patents/data/coverage

[37] https://www.epo.org/en/searching-for-patents/business/patstat

The authors and research teams did their best to prevent patent applications of a military nature from being retrieved by the queries and included in the dataset. However, due to the dual-use nature of space applications, especially rocket technology, it should be noted that the dataset might contain such patent documents or might miss certain patents with civil applications within the analysis.

Figure 6

This technology map shows a summary of the concepts analysed in this report.



2. Analysis of patents

For this study a total number of 4559 patent families filed at 52 patent authorities have been identified with applicants registered in 43 countries and inventors residing in 53 countries. A patent family is a collection of patent applications covering the same invention filed by the applicant in different countries. This report also uses a stricter concept of patent families called international patent families (IPFs). This concept excludes all single national patent families that have only been filed in the country of the applicant[38]. Patent families with applications having applicants or inventors from different countries were also considered to be international patent families. EP and WO filings[39] as well as any other regional office filings are by default IPFs. Of the 4559 patent families used in this report, 1178 are IPFs (about 26%), grouping a total of 4626 unique patent applications filed in 52 different patent jurisdictions.

This section is structured into two major parts. The first part analyses trends in the international patent landscape regarding propulsion. The second part delves deeper into specific propulsion principles, such as chemical, electric, or alternative propulsion concepts.

2.1. Breakdown by region

The breakdown by region is also split into two parts: the first part investigates the global applicant landscape, while the second part examines how the European landscape is positioned in comparison to the global landscape.

2.1.1. International breakdown

Given that propulsion is a fundamental enabler of most space applications, as revealed by the first chapter, it is not surprising that patent filings in this area increased considerably between 2003 and 2022, as shown in Figure 7. This is in line with the general increase in space activities observed in recent years. Similar to previous patent studies, the first major observation is that China's prominence is very pronounced – accounting for roughly 38% of all 4559 patents filed in 2003 - 2022. Considering 2022 alone, China's share even increases to 65%, indicating that the domain is of strategic importance to Chinese policymakers. Moreover, it should be noted that although China only tops the total number of filings in electric propulsion, Chinese applicants are also towards the top in lists of applicants in other fields of propulsion. This indicates a rather diverse patent landscape in China, whereas in the patent landscapes of other countries or regions (US, EU or Japan) applicants tend to be more concentrated on a limited number of fields.

Furthermore, Chinese and Indian aerospace industries have conducted an increasing number of very successful space activities in recent years, leveraging their significant technical advancements. These two nations have undoubtedly demonstrated considerable progress in their capabilities and positioned themselves as notable players in the international market. Unfortunately, no data for Indian patent filing activities could be obtained for this report (see chapter 1.6).

After China, the other top four patent-filing countries in 2022 were the US, Germany, Japan and France.

While Europe has traditionally maintained a leading position in this sector, primarily due to its rich heritage of flight-proven designs and advanced manufacturing techniques, it is crucial for European aerospace entities to view the emerging competencies of China and India not merely as competition, but as an incentive for domestic growth and advancement.

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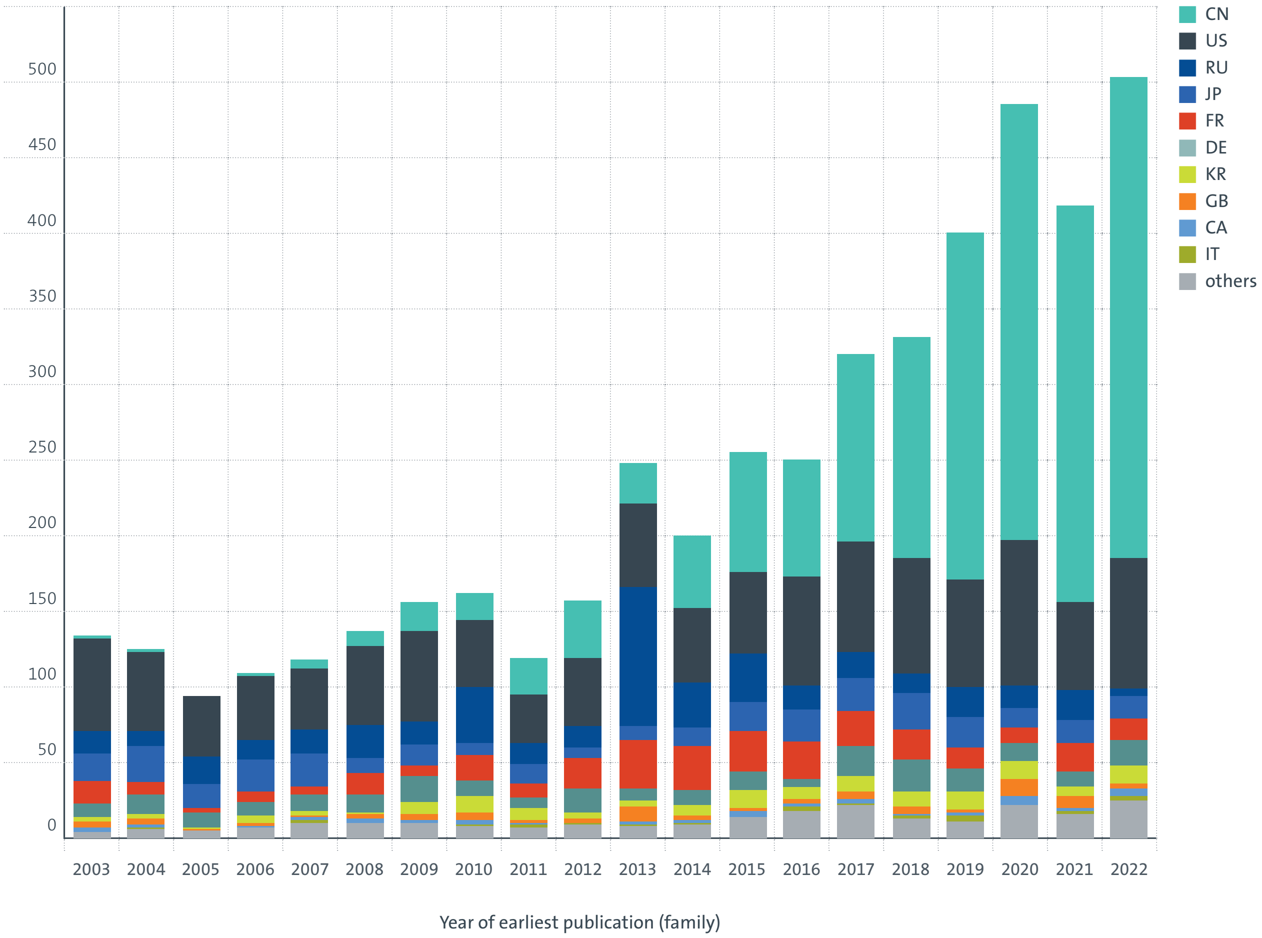
[38] Applicant countries and filing authorities are abbreviated throughout the report according to WIPO STANDARD ST.3: https://www.wipo.int/standards/en/pdf/03-03-01.pdf

[39] EP denotes filings at the European Patent Office and WO those at the World Intellectual Property Organization

Figure 7

All propulsion patent families by applicant country

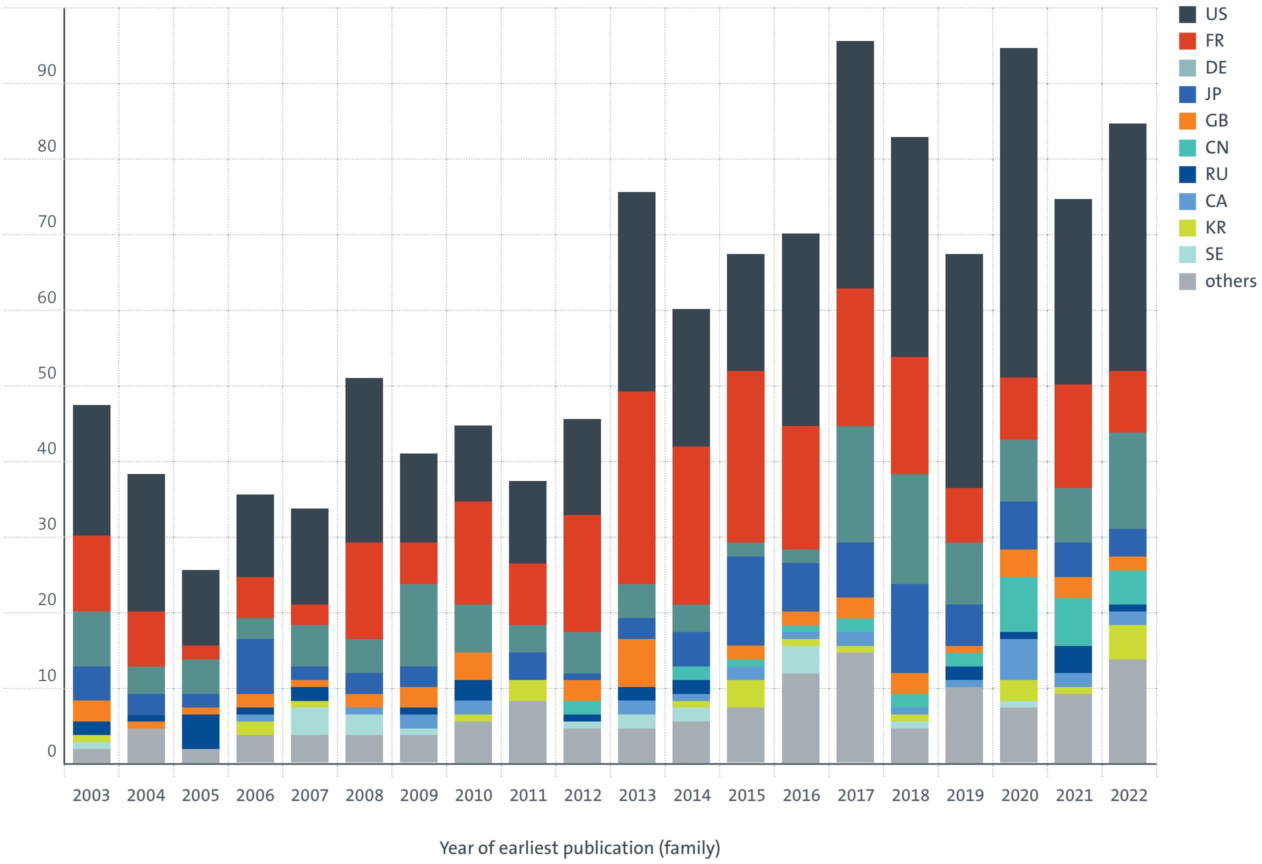


The second major observation considering the overall data is that over two thirds (74%) of patents are only filed nationally, as is evident in Figure 9.

In fact, if only patents filed internationally between 2003 and 2022 are considered, there is only moderate growth in overall applications (6.1% average annual growth rate vs 9.2% when also considering national patents). Considering solely international filings, the top countries in 2022 were more evenly distributed with the US leading (43%), followed by Germany (17%), France (11%), China (6%), South Korea (6%) and Japan (5%).

Figure 8

International patent families by applicant country



Combining both initial observations, it can be deduced that the overall filing increase in respect of propulsion systems is mainly driven by Chinese national patent filings. However, the dominance of Chinese filing activity diminishes when the number of international filings is analysed.

An additional observation regarding Chinese patent applications is that the country's patent families are also increasingly cited: either by the applicants or by the examining patent offices. The number of forward citations of a patent family can be viewed as an indicator for the quality and impact of the underlying invention. We observe that up until 2007, it was primarily patents filed by US and JP applicants that were cited, and the number of individual citations was rather high. From 2008 onwards, we see a rapid increase in the number of patents filed by CN applicants being cited.

When filtering cross-national citations (Fig 10) we can see that the high number of Chinese citations is mainly between patent families of domestic applicants, with only a few cross-national citations.

Figure 9

International vs all patent families (including domestic)

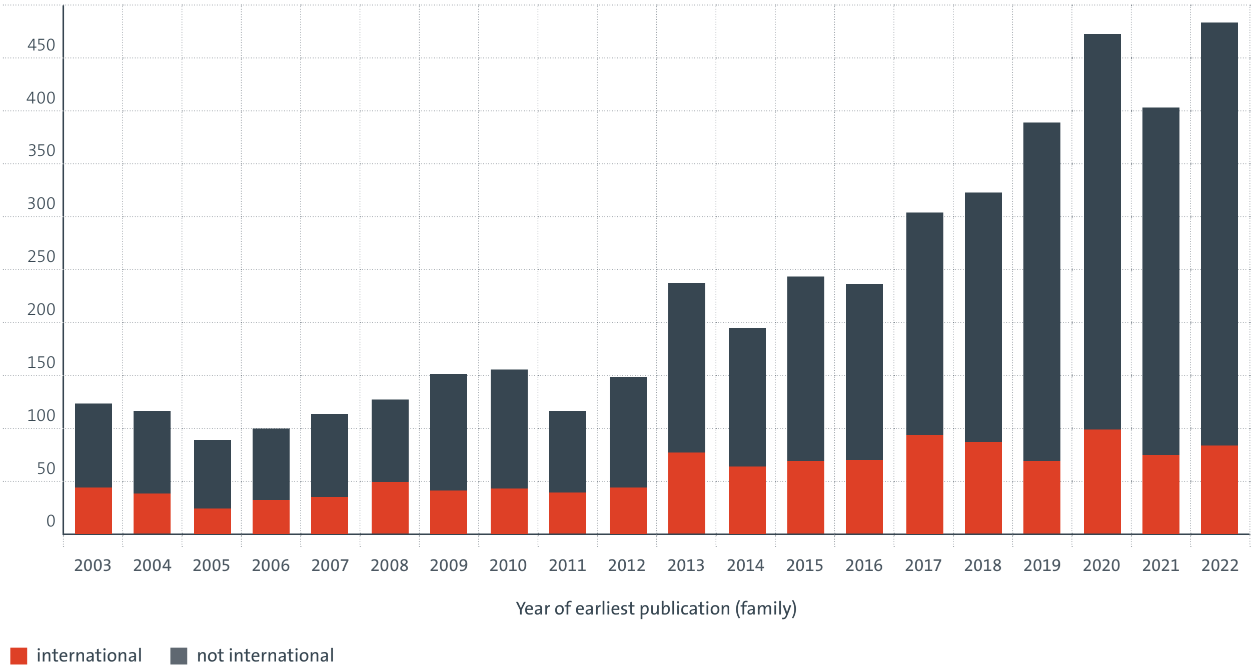


Figure 10

Top applicant countries by forward citation

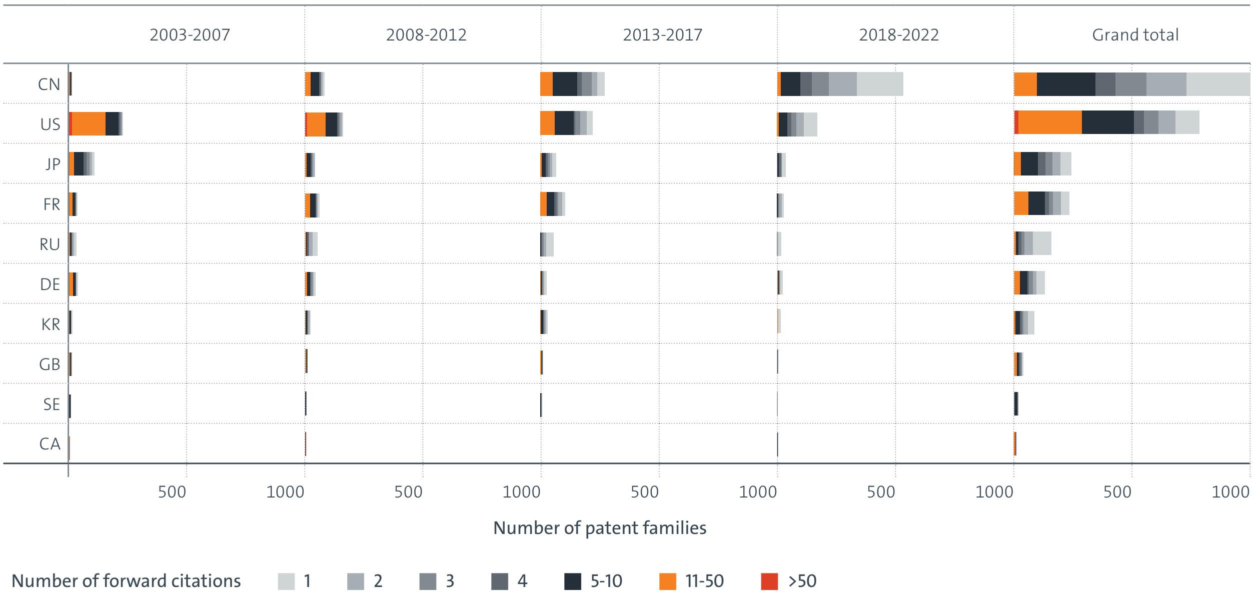
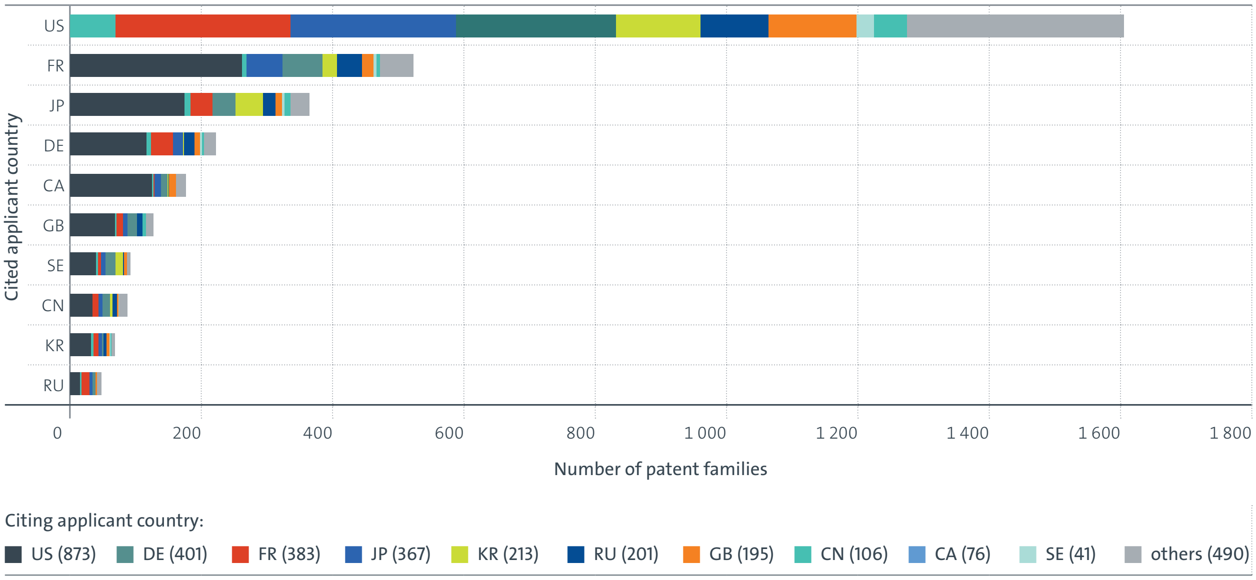


Figure 11

Cross-national citations



US applicants are most frequently the subject of cross-national citations. Technology givers, who are the most-cited applicant countries, are mostly from the US followed by FR, JP, DE and CA. Technology receivers, identified by citing patent families, are primarily from the US followed by DE, FR, and JP.

Following the breakdown by country, the respective top players originate from these countries as well. Chinese players stood out in particular, not only due to their being the top players but also because they represent a unique set of institutions. While in other countries, patents are almost always filed by large private companies, in China the major patent portfolios in space propulsion are applied for by research entities and universities. In terms of the number of patent applications, the top two players overall are the Harbin Institute of Technology and the Beihang University, both located in the northern part of China. They are followed by Airbus, Safran, and Boeing. However, it should be noted that in Figure 12 the numbers of patent families given are for both international and national filings. Also, the ranking does not take into account whether patents have been granted or not.

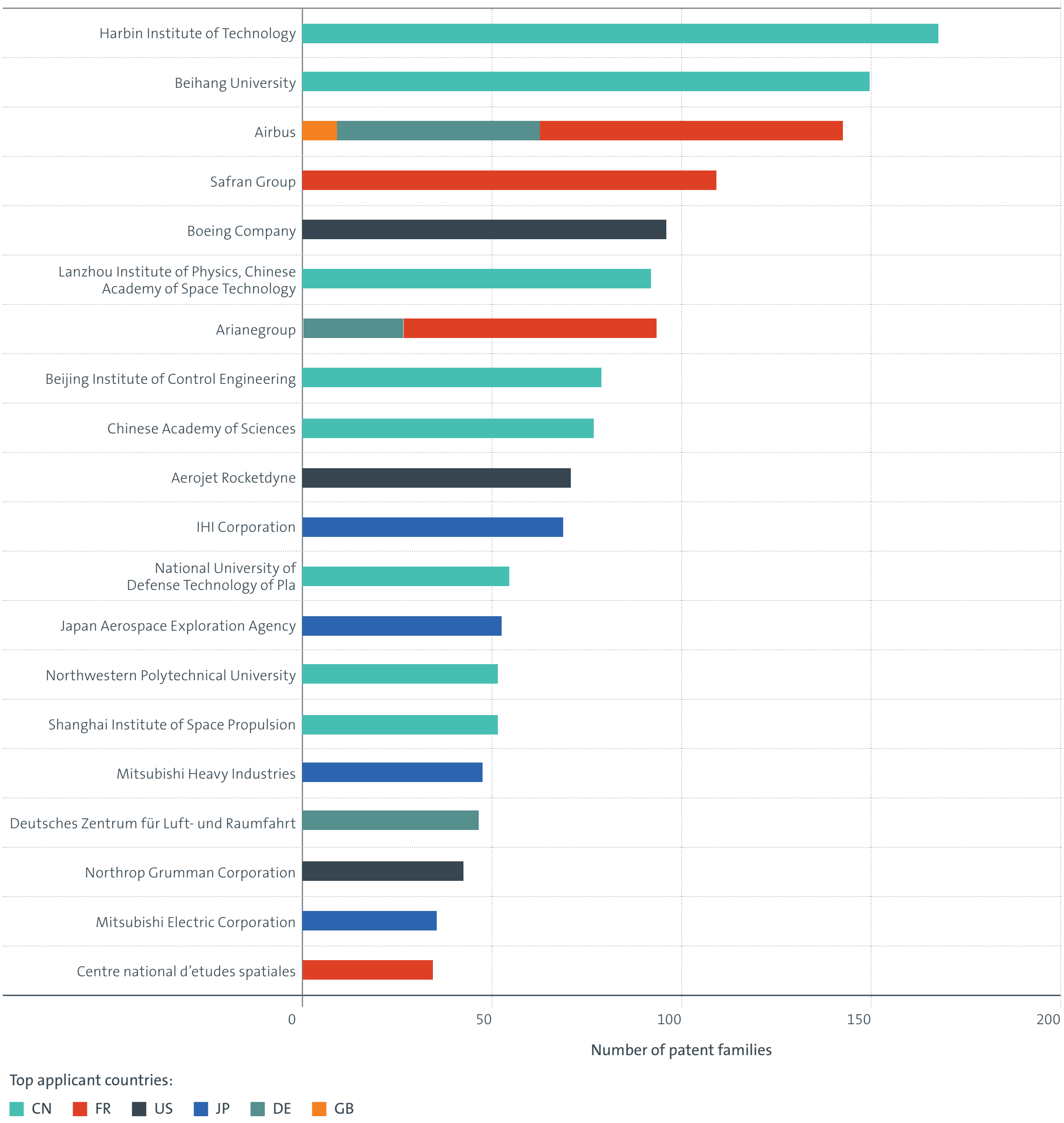
Top Chinese applicants

The **Harbin Institute of Technology**, founded in 1920 as a Sino-Russian Industrial School, was the first ever school to introduce university-level education in astronautics in China in its School of Astronautics. It is very active in international scientific cooperation, especially with the Russian Federation, and it manufactures as well as operates its own satellites. Today, it is affiliated with the Chinese Ministry of Industry and Information Technology

The **Beihang University** has a particular aerospace focus and is widely considered to be one of the top engineering universities in China. It too launches and operates its own satellites.

Figure 12

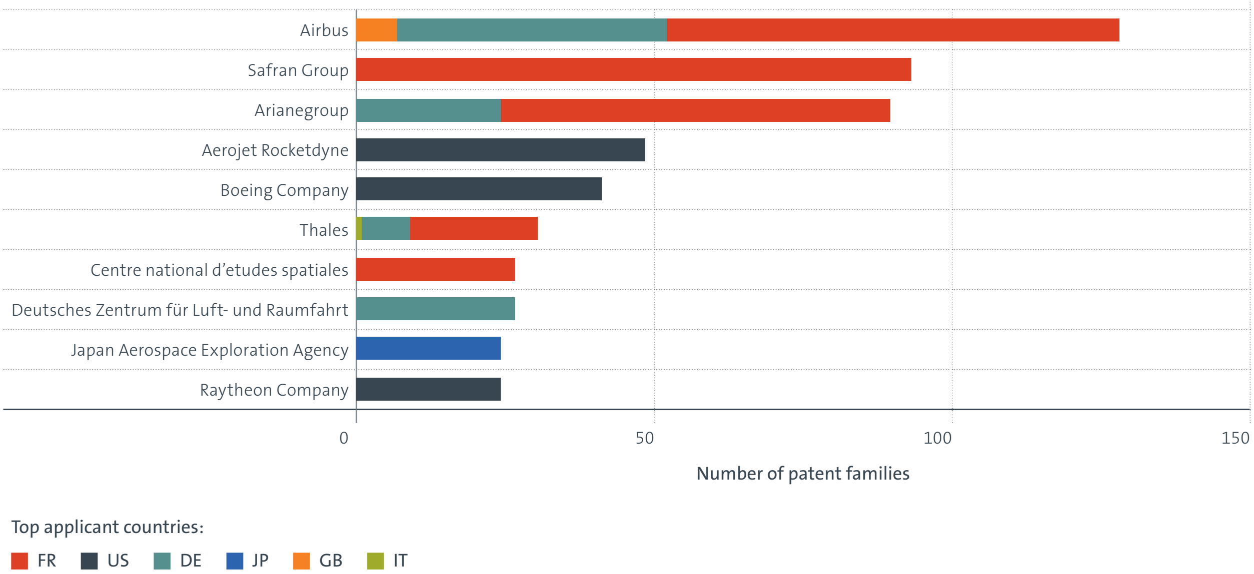
Top applicants – all patent families



As previously stated, the US is the leading nation in terms of internationally filed patents. However, there are only 3 US applicants in the top 10 (Aerojet Rocketdyne, Boeing and Raytheon). In contrast the European applicants are well represented as can be seen from Figure 13, with French and German companies such as Airbus, Safran, the Ariane Group and Thales as well as public players such as CNES or DLR. Thus, it can be concluded that patent activity regarding propulsion is more concentrated with few players in Europe, compared to the US, which builds on a higher number of smaller applicants.

Figure 13

Top applicants – international patent families



2.1.2. Europe-specific findings

Comparing Europe (defined as the EPC member states) to other top applicant countries, it is apparent that the continent is reasonably well-represented with 36.7% of all patents being filed by European applicants if only internationally filed patents are considered. However, if nationally filed patents are also considered, Europe's share has decreased greatly over the last 20 years and only accounted for 10% in 2022.

Figure 14

National filings vs International Patent Family (IPF) by country

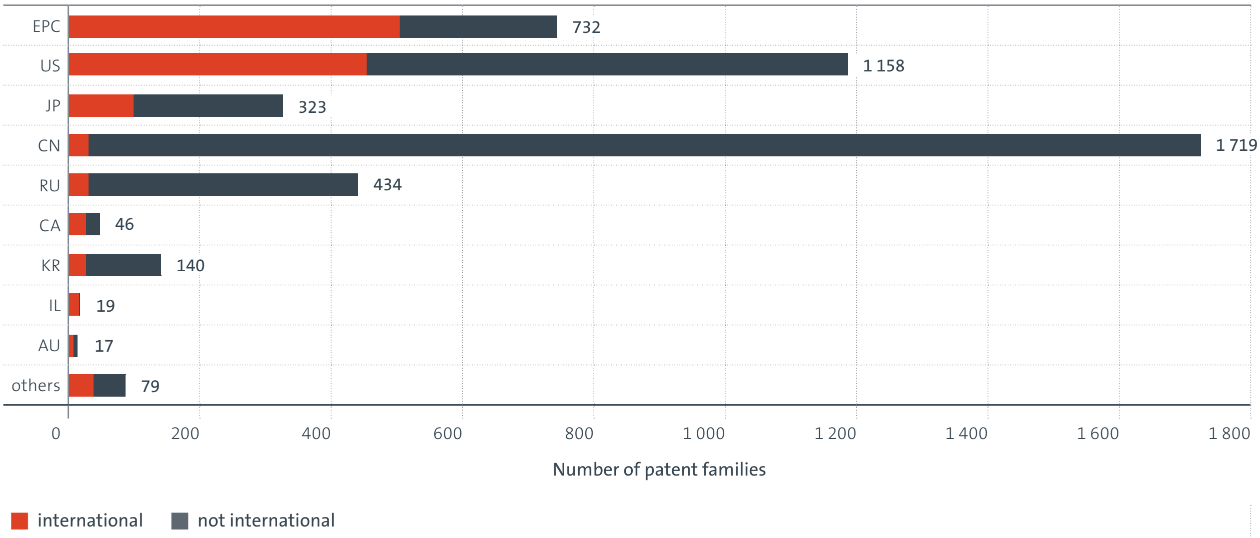
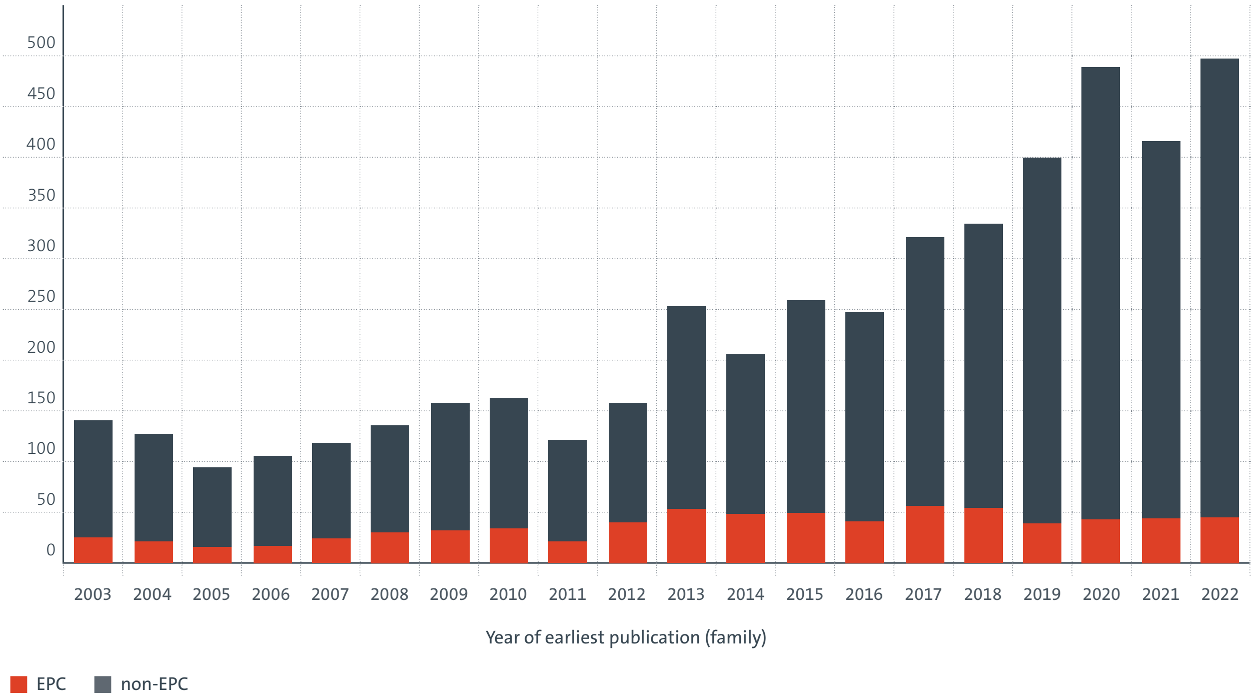


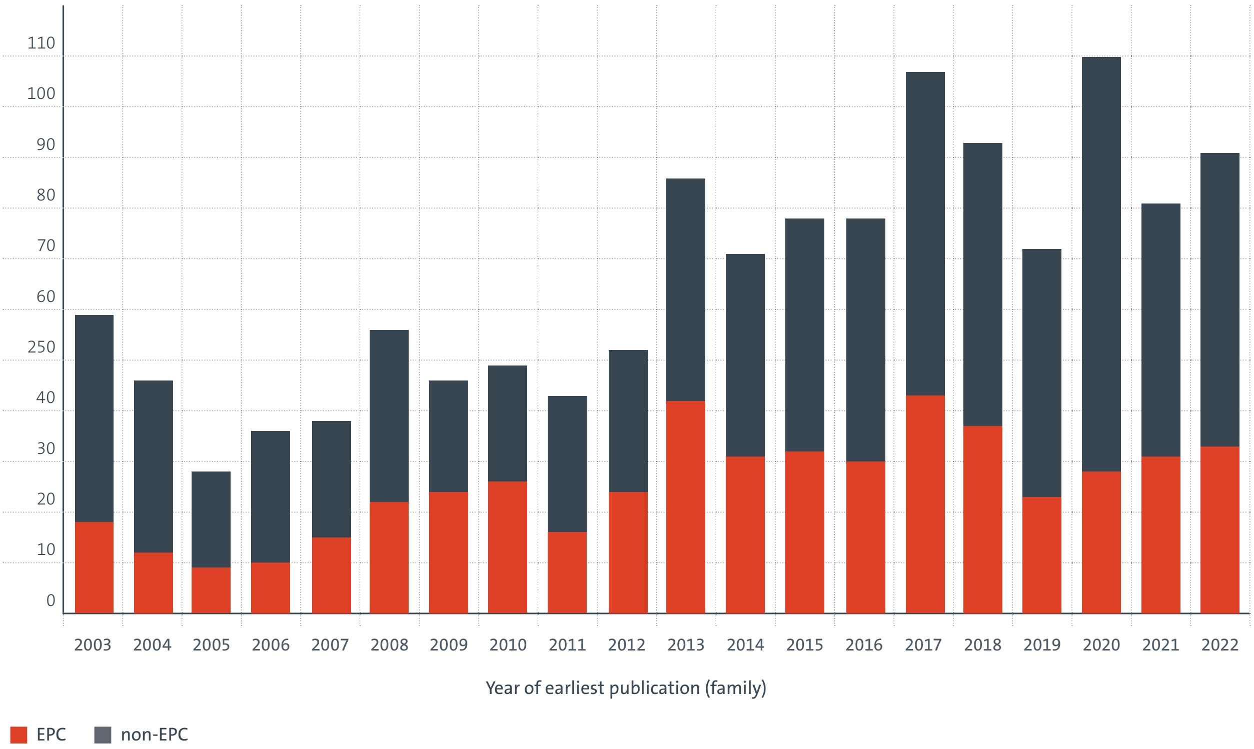
Figure 15

Patent families EPC applicants vs rest of the world; all filings (top) vs international patent families IPF (bottom)

EPC applicants vs all applicants



EPC applicants vs all applicants (IPF)



However, EPC member countries are not only losing relative share, but there is also an absolute slowdown in propulsion-related patent filings from the continent over the last 10 years. While filings grew by an annualised average of 6.3% between from 2003 until 2012, there was an average annual decrease of about 1.8% between 2013 and 2022 as can be seen from Figure 15 for all patent families. Similarly, there was also a growth of 8.1% and a decline of 2.7% for international patent families over the same respective time periods

This reflects broader trends in many sectors, especially technological, where Europe has lost ground over the last few decades caused by the emergence of new players and a lack of a coherent European response. Europe has historically been at the forefront of transformative innovation, leading the way in developments that have shaped entire centuries. However, in recent decades, it appears to have deviated somewhat from its pioneering spirit. According to a Joint Research Centre report from 2019, the change in global share in manufacturing value chains was –11.4 percentage points between 2000 and 2014 for the EU and +13.7 for China[40] as can be seen in Figure 16.

Figure 16

World share in Global Value Chains;
change in percentage points 2000-2014[39]

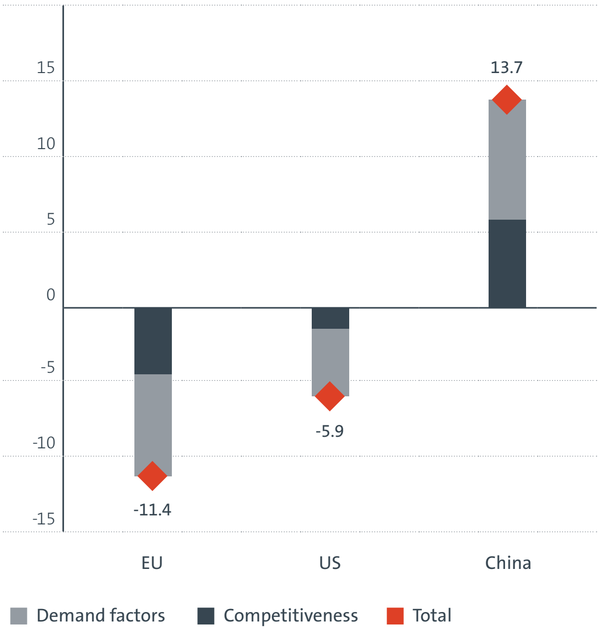
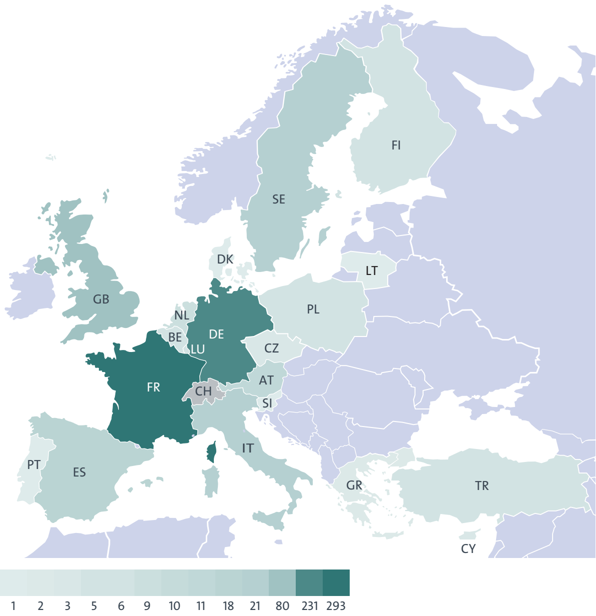


Figure 17

National and international patent families from EPC applicant countries



This shift is most apparent in the realm of digital development, where Europe has missed crucial opportunities in areas such as the Internet revolution, artificial intelligence, and semiconductor technology. For example, in 1990, Europe was home to almost half of global chip manufacturing, but by 2020 its share had fallen to less than 10%.

Zooming in further on Europe, it can be seen that space propulsion patent activity is primarily located in countries with a long heritage in upstream space activities[41], namely Germany and France.

Taken together, both countries account for more than two thirds (71%) of national and international patent families in Europe. This trend exceeds the distribution of economic activity on the continent because in terms of GDP Germany and France taken together only accounted for roughly one third (32%) of Europe's GDP in 2022[42]

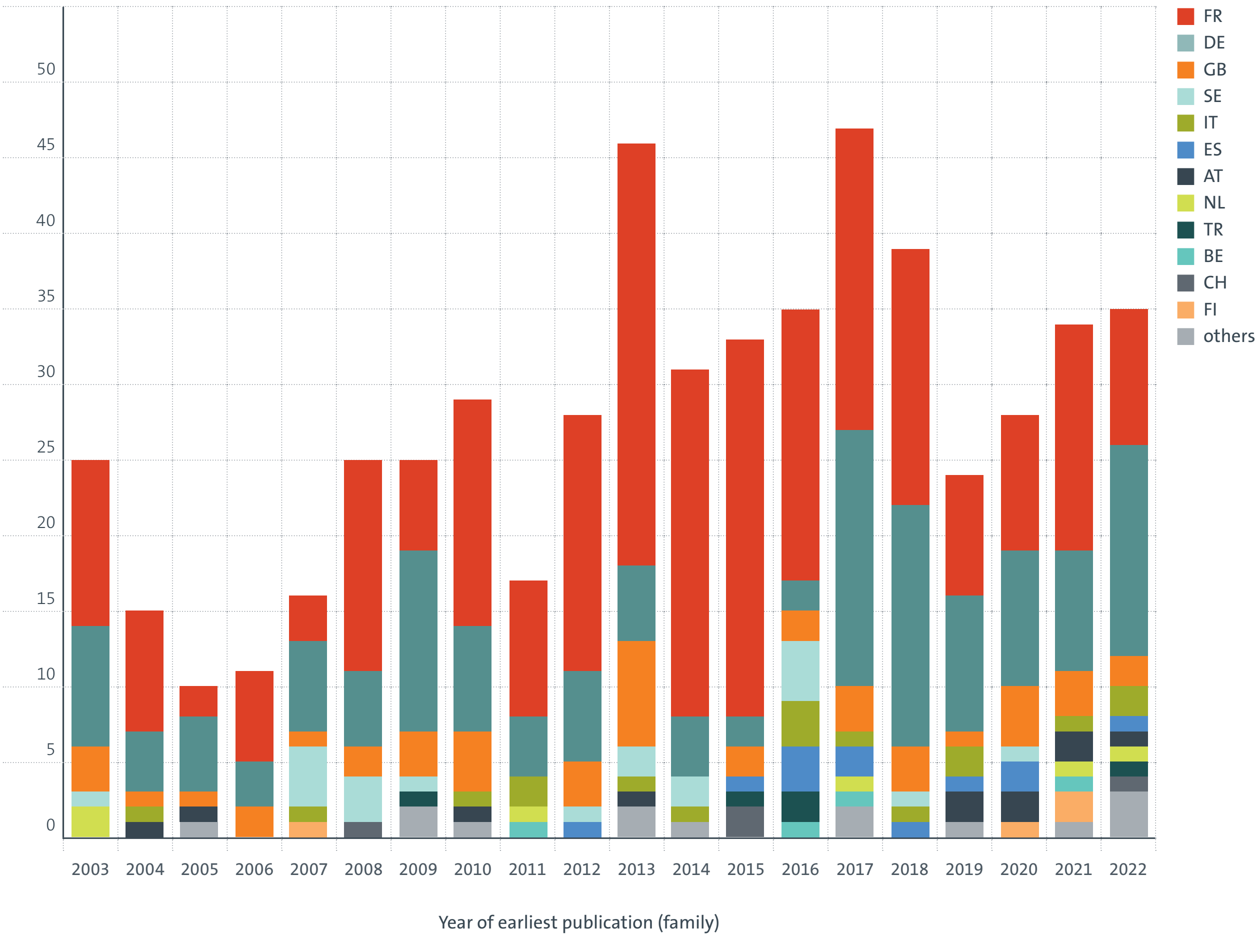
[40] https://publications.jrc.ec.europa.eu/repository/handle/JRC116516 (Figure 1)

[41] The space industry is split into two pillars: upstream and downstream. While upstream capabilities entail sending objects into space as well as space exploration, downstream capabilities include activities that use space applications on earth.

[42] Trading economics 2024 https://tradingeconomics.com/country-list/gdp?continent=europe

Figure 18

Patent activity in Europe



2.2. Divided by propulsion principles

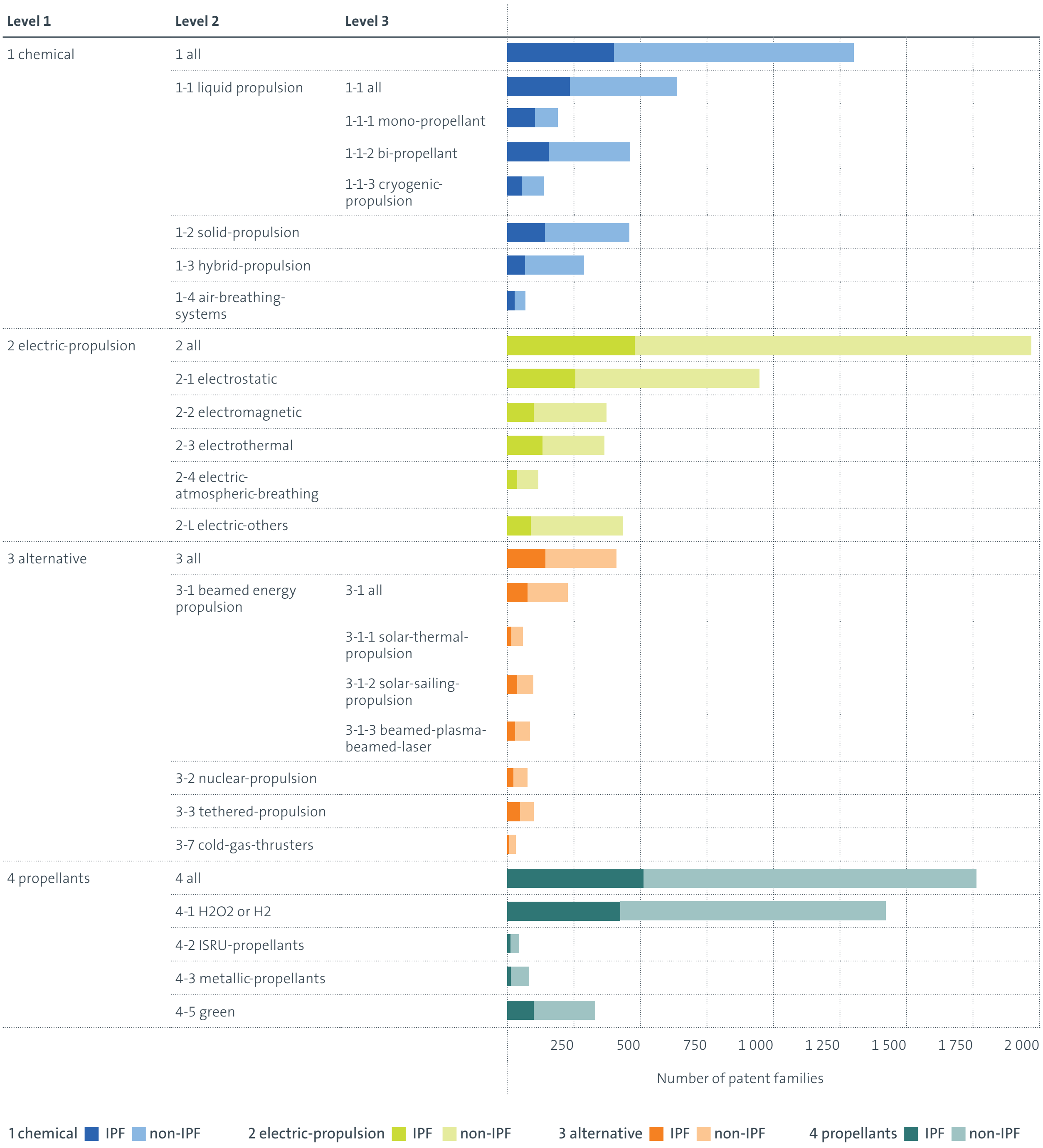
After investigating some overall trends, this chapter delves deeper into the specifics of different propulsion principles and the patent landscape surrounding them.

2.2.1. Overall picture

The following chapter is divided into different sections, namely electric propulsion, chemical propulsion, alternative propulsion concepts and propellants.

Figure 19

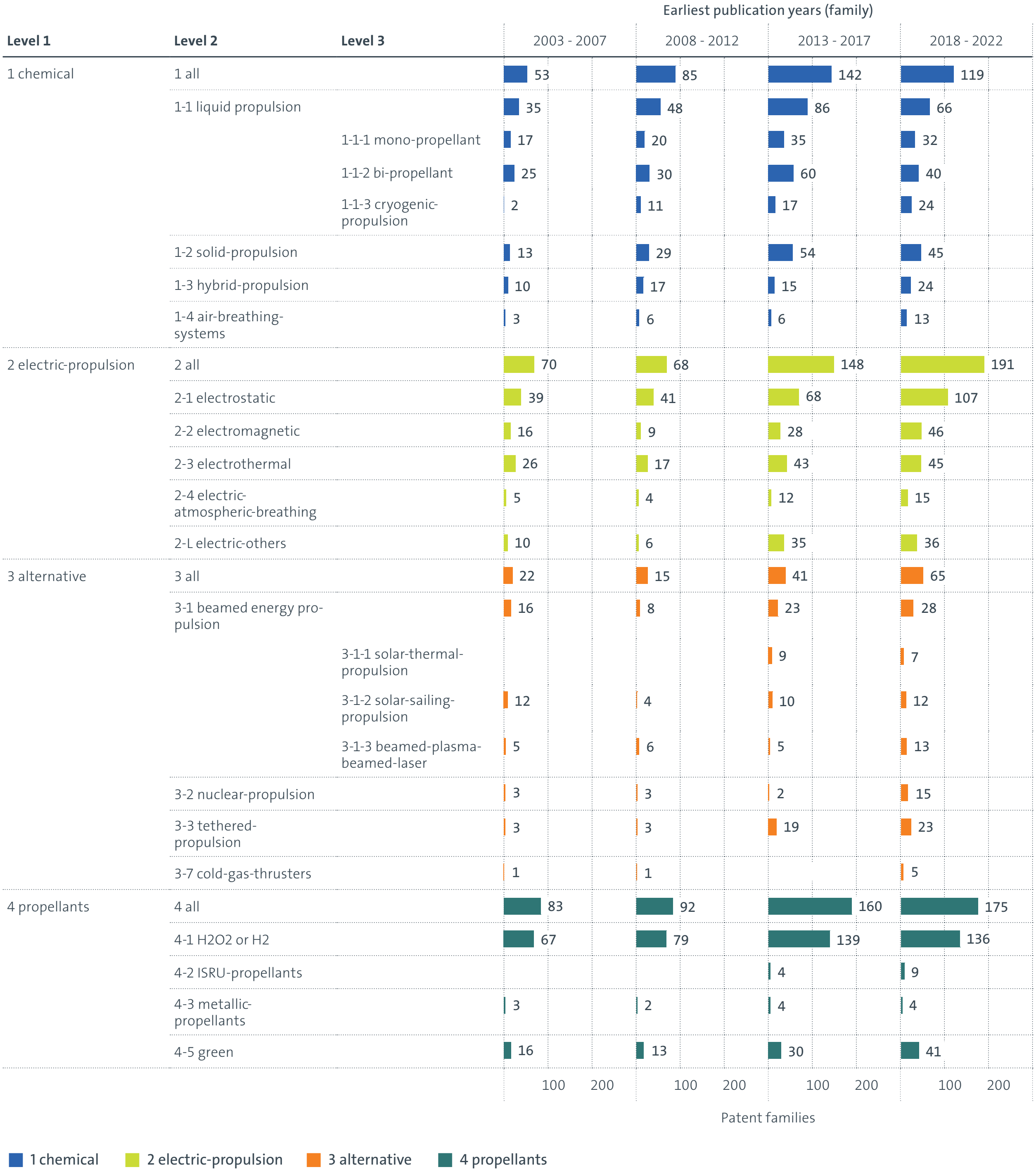
Technology map



Presenting this data per time period makes it possible to see development trends:

Figure 20

Technology map for internationally filed patents over time



Figures 19 and 20 present a diverse picture of propulsion technology with the main concepts like liquid chemical, electrostatic, as well as hydrogen propellant growing over time. This is true both when investigating nationally or internationally filed patents. From the period 2013 - 2017 onwards electric propulsion systems have overtaken chemical propulsion systems.

Specialisation Index

The OECD specialisation index (revealed technology advantage) compares the share of an economy's patents in a specific technology relative to the share of total patents[43]. A specialisation index of 1 means that the representation of this technology in the country's portfolio is the same as for all countries, greater one means that more patents are filed in this area compared to other countries.

Figure 21

Specialisation index for applicant countries

Level 1	**Level 2**	**Level 3**	CN	US	RU	JP	FR	DE	GB	others
1 chemical	1 all		0,8	1,1	1,0	1,3	1,1	0,8	0,7	1,2
	1-1 liquid propulsion		0,6	1,2	0,9	1,2	1,4	1,1	0,6	1,2
		1-1-1 mono-propellant	0,0	2,1	0,0	1,2	1,0	1,5	1,3	1,2
		1-1-2 bi-propellant	0,8	1,0	1,1	1,1	1,2	1,0	0,8	1,3
		1-1-3 cryogenic-propulsion	0,4	1,3	0,7	1,1	2,4	1,2	0,4	1,2
	1-2 solid-propulsion		0,6	1,2	1,2	1,7	0,9	0,4	1,0	1,1
	1-3 hybrid-propulsion		1,3	0,9	0,5	0,9	0,6	0,4	0,7	1,4
	1-4 air-breathing-systems		0,6	1,4	0,9	0,4	0,8	1,5	1,4	1,6
2 electric-propulsion	2 all		1,5	0,8	0,9	0,8	0,8	0,8	0,9	0,7
	2-1 electrostatic		1,4	0,9	0,9	0,8	1,1	0,7	1,1	0,6
	2-2 electromagnetic		1,4	1,0	0,4	0,5	0,5	1,2	1,1	0,8
	2-3 electrothermal		0,8	1,3	0,4	1,1	0,6	0,5	2,2	1,2
	2-4 electric-atmospheric-breathing		1,4	1,3	0,1	0,2	1,0	0,0	1,6	0,6
	2-L electric-others		1,6	0,5	1,3	0,8	0,9	1,1	0,2	0,6
3 alternative	3 all		0,6	1,5	0,6	0,5	0,8	1,6	1,9	1,1
	3-1 beamed energy propulsion		0,5	1,5	0,7	0,6	0,7	2,1	2,4	1,0
		3-1-1 solar-thermal-propulsion	0,7	1,6	0,6	1,2	0,2	0,6	1,7	1,0
		3-1-2 solar-sailing-propulsion	0,4	1,2	0,9	0,4	1,4	4,4	1,5	0,8
		3-1-3 beamed-plasma-beamed-laser	0,4	1,9	0,4	0,3	0,2	0,8	4,0	1,4
	3-2 nuclear-propulsion		0,7	1,9	0,5	0,0	0,5	1,4	1,8	0,6
	3-3 tethered-propulsion		0,4	1,4	0,5	0,9	1,5	1,0	2,3	1,6
	3-7 cold-gas-thrusters		1,8	0,9	0,0	0,4	0,4	0,6	0,0	1,0
4 propellants	4 all		0,9	0,8	1,5	1,2	1,1	1,1	0,8	1,1
	4-1 H2O2 or H2		0,8	0,8	1,7	1,2	1,3	1,3	0,9	1,0
	4-2 ISRU-propellants		1,5	1,6	0,3	0,3	0,3	0,0	0,0	0,2
	4-3 metallic-propellants		1,1	1,0	0,6	2,7	0,3	0,2	0,0	1,0
	4-5 green		1,2	1,0	0,4	0,7	0,3	0,6	1,2	1,7

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[43] https://doi.org/10.1787/9789264268821-en

The country specialisation based on both international and national patent families shows that Chinese applicants have a technology advantage in electric propulsion, cold gas thrusters and ISRU propellants, while US applicants have an advantage in mono-propellants, beamed plasma beamed laser propulsion and nuclear propulsion, Japanese applicants in metallic propellants, French applicants in cryogenic propulsion, German applicants in solar sailing propulsion and British applicants in beamed plasma beamed laser, nuclear and tethered propulsion. It should be noted that the specialisation calculation over-emphasises effects for areas with smaller numbers, i.e. filings from smaller filing countries or lesser used concepts typically have a more pronounced deviation from the average distribution.

2.2.2. Chemical propulsion

Chemical propulsion involves concepts for liquid propulsion, solid propulsion and hybrid propulsion. It represents the most traditional principle of in-space and launcher propulsion used for a wide variety of applications and platforms. A particular observation that can be made with respect to patent filing data is the correlation between the increase in launch activities and filing activities. This can be seen as a steady, linear increase in patent filings for chemical propulsion between 2003 and 2023 in Figure 22, matched by the development of the launch market, represented by the total number of launches over the same timeframe (Figure 23).

Figure 22

Number of patent families for chemical propulsion plotted against time

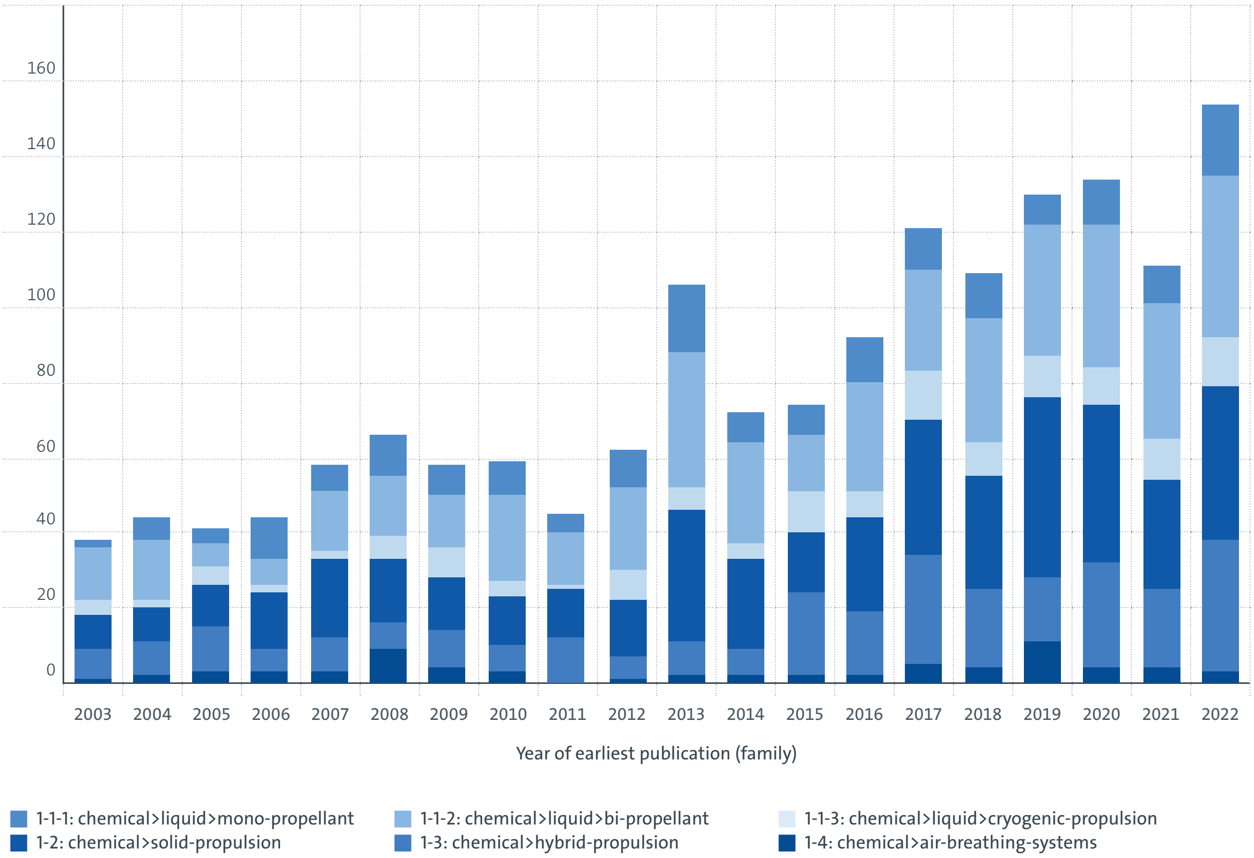
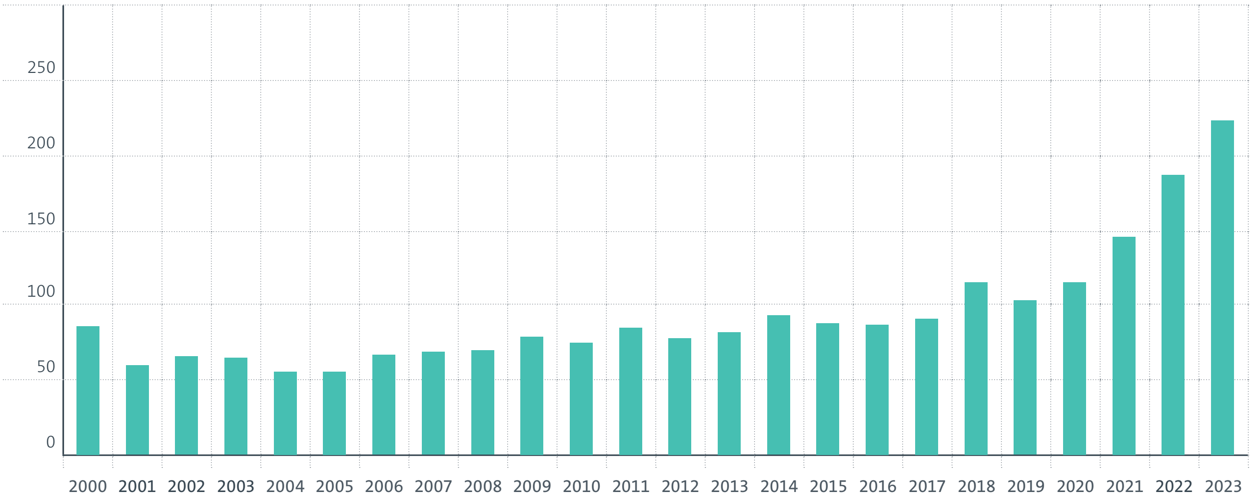


Figure 23

Total number of launches 2000-2023 (ESPI launch database 2024)



The dataset also shows that not only are the trends for patent filings and launches aligned, but that the countries dominating the launcher market are also responsible for the majority of patent filings for chemical propulsion concepts. Similarly to the traditional launcher market, the United States and China are top in both charts, filing most national and international patent applications.

Figure 24

Patent families in chemical propulsion by country

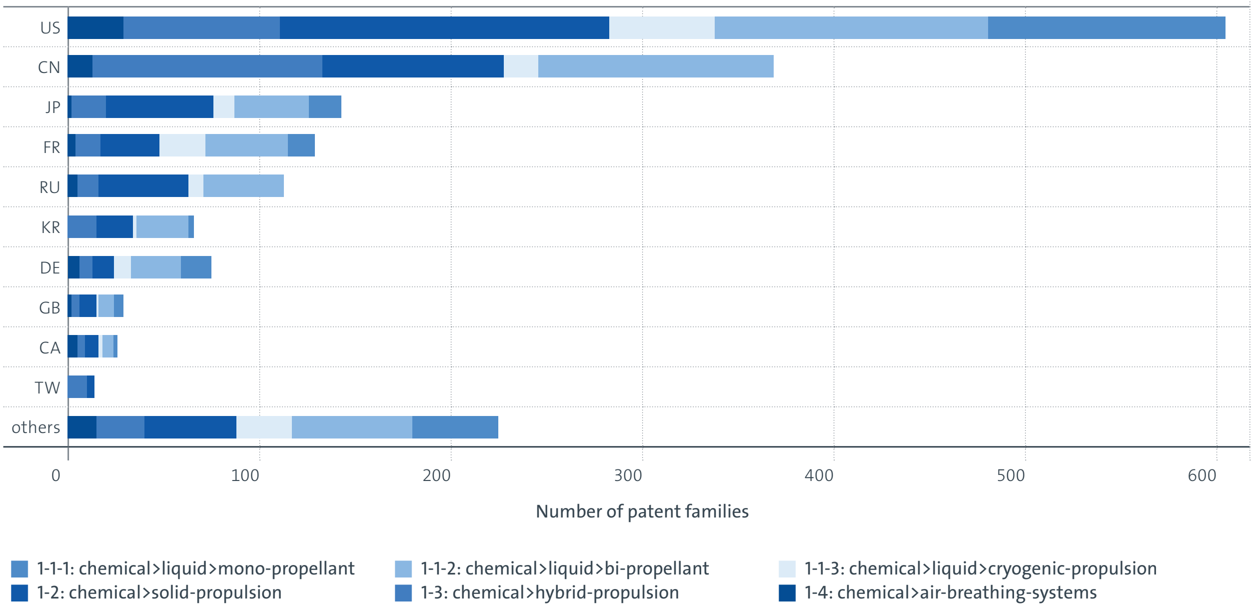
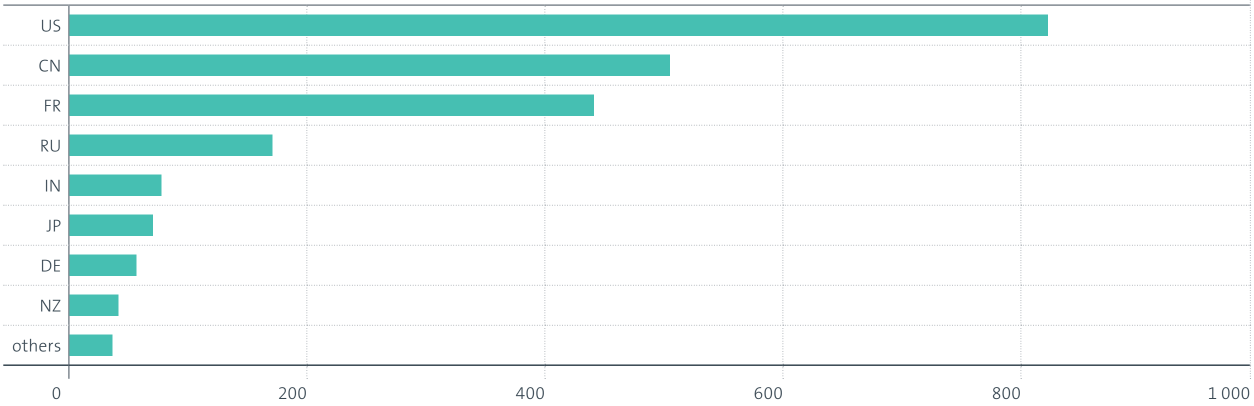


Figure 25

Number of launches by launch service provider country 2000-2023 (ESPI launch database 2024)



While France seems overrepresented in the launch data relative to its number of patent filings, it needs to be taken into account that the company Arianespace acts as launch service provider for the Ariane and Vega rocket families which are also developed and manufactured in Germany and Italy. Furthermore, it should be taken into account that SpaceX only very recently started filing patents for launch vehicle technology, but accounted for roughly 43% of launches in 2023. This also contributes to the observation that the rise in total launches (Figure 23) is even more pronounced than the rise in chemical propulsion patents (Figure 22).

Solid vs liquid propulsion

Solid and liquid chemical propulsion concepts are the most widely used means of propelling spacecraft and launchers. The choice of a concept or a combination of concepts is driven by the specific requirements of the mission, i.e. the necessary performance and precision, as well as costs, complexity, manufacturability, reliability and safety.

Solid propulsion concepts provide a high thrust-to-weight ratio with a simple and reliable design. As such they are suitable for booster stages of space launch vehicles or as a supplement to liquid propulsion concepts. Launchers designed for lifting smaller payloads, such as Europe's VEGA or China's Long March 11 even use solid concepts as a primary means of propulsion. Nevertheless, it should be noted that these characteristics also make solid propulsion concepts favourable for military applications.

Liquid propulsion concepts distinguish themselves because of the associated high efficiency and design options for throttle control and re-ignition that offer flexibility and controllability of upper stages and spacecraft in orbit.

The collected patent data, as shown in Figure 26, reveals increasing but fluctuating filing activity. Considering hybrid propulsion concepts, an increase in filing activity can also be seen, but the absolute annual filing numbers are still considered low.

Figure 26

Solid, liquid and hybrid propulsion concept filings plotted over time

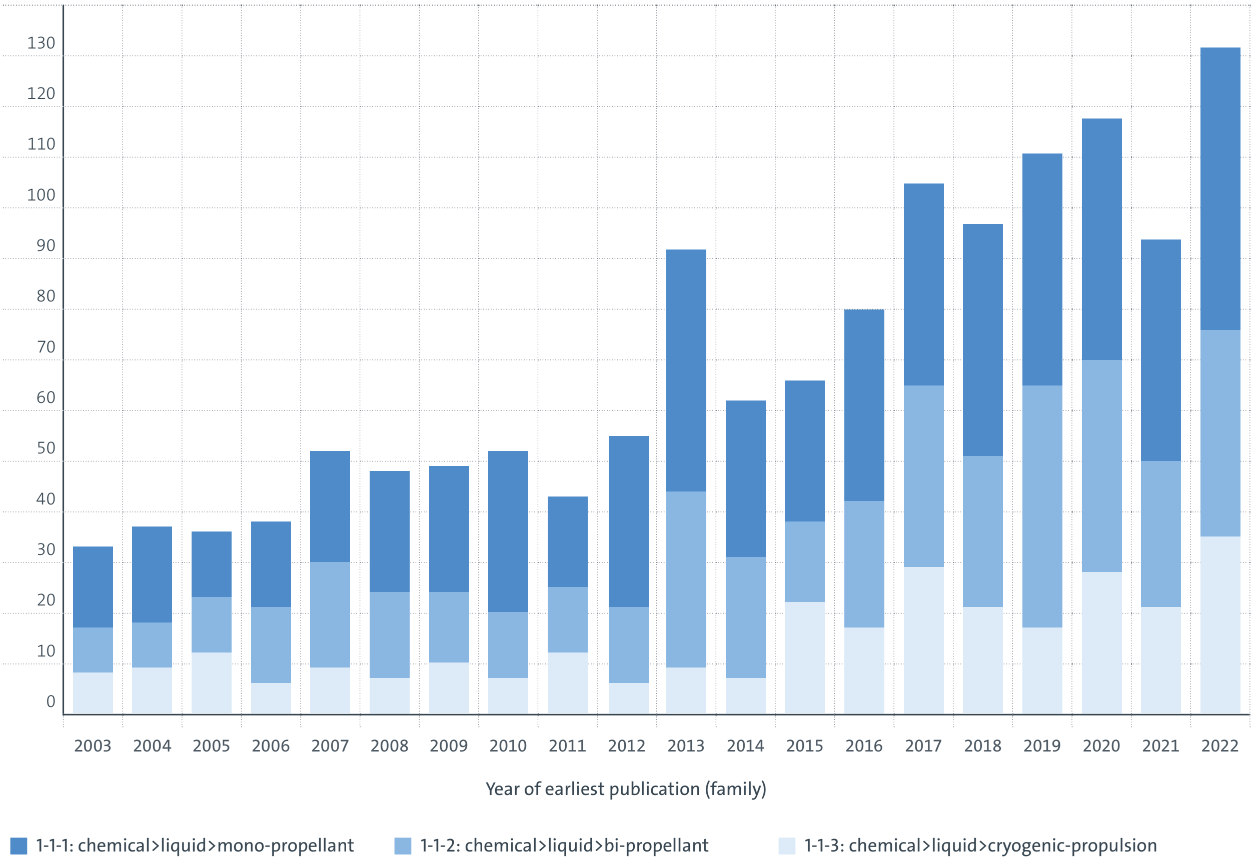
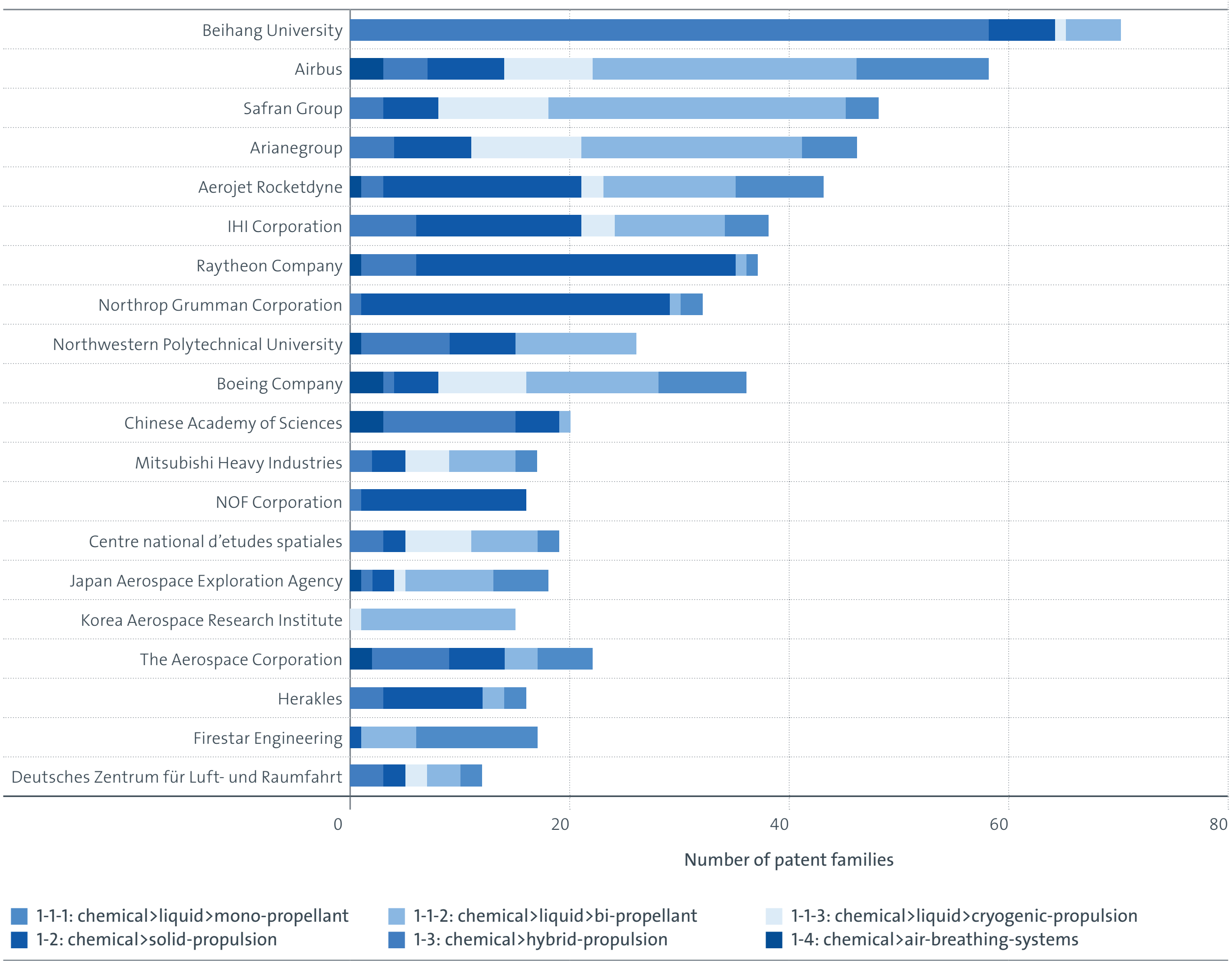


Figure 27

Top applicants – chemical propulsion



The top applicants in this domain reveal international activity and a range of differing focuses. Notably, Beihang University and the Chinese Academy of Sciences apply for patents with a focus on hybrid propulsion applications, while US and Japanese companies predominately manage solid propulsion applications (e.g. Raytheon, Northrup Grumman, NOF and IHI). In Europe the focus of the top applicants appears to be on the bipropellant sub-concept.

2.2.3. Electric propulsion

Electric propulsion patent filings have increased the most over the last 20 years, especially due to increased filing by Chinese players, who contributed to 67% of all patents filed in this field in 2022. It consists of different concepts, namely electrothermal, electrostatic and electromagnetic. Additionally, inventions related to atmospheric-breathing electric propulsion have grown into a separate, transversal category. The increase in electric propulsion has mainly been driven by substantial advancements in solar array technology, in which the specific power generated on-board spacecraft has increased from 30 to 100 W/kg[44] over the last 25 years, with future increases to be expected. Figures 28 and 29 provide an overview of activities in electric propulsion both by country and concept-specification for all patents, both nationally and internationally filed.

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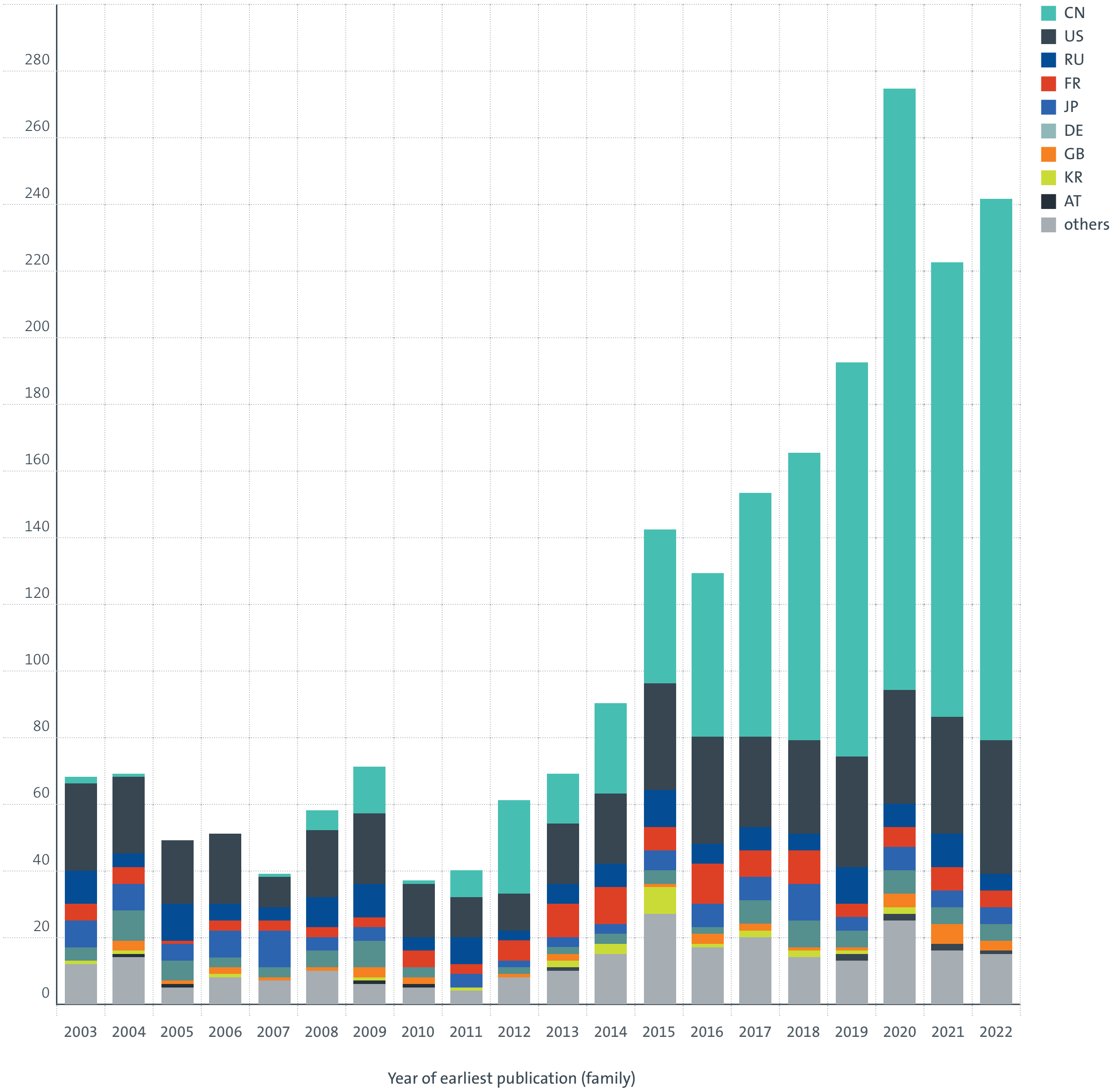
[44] https://hpepl.ae.gatech.edu/sites/default/files/files/Review%20of%20HP%20ES%20ET%20EP_JPP%20Nov%202022.pdf

Figure 28

Top applicant countries in electric propulsion

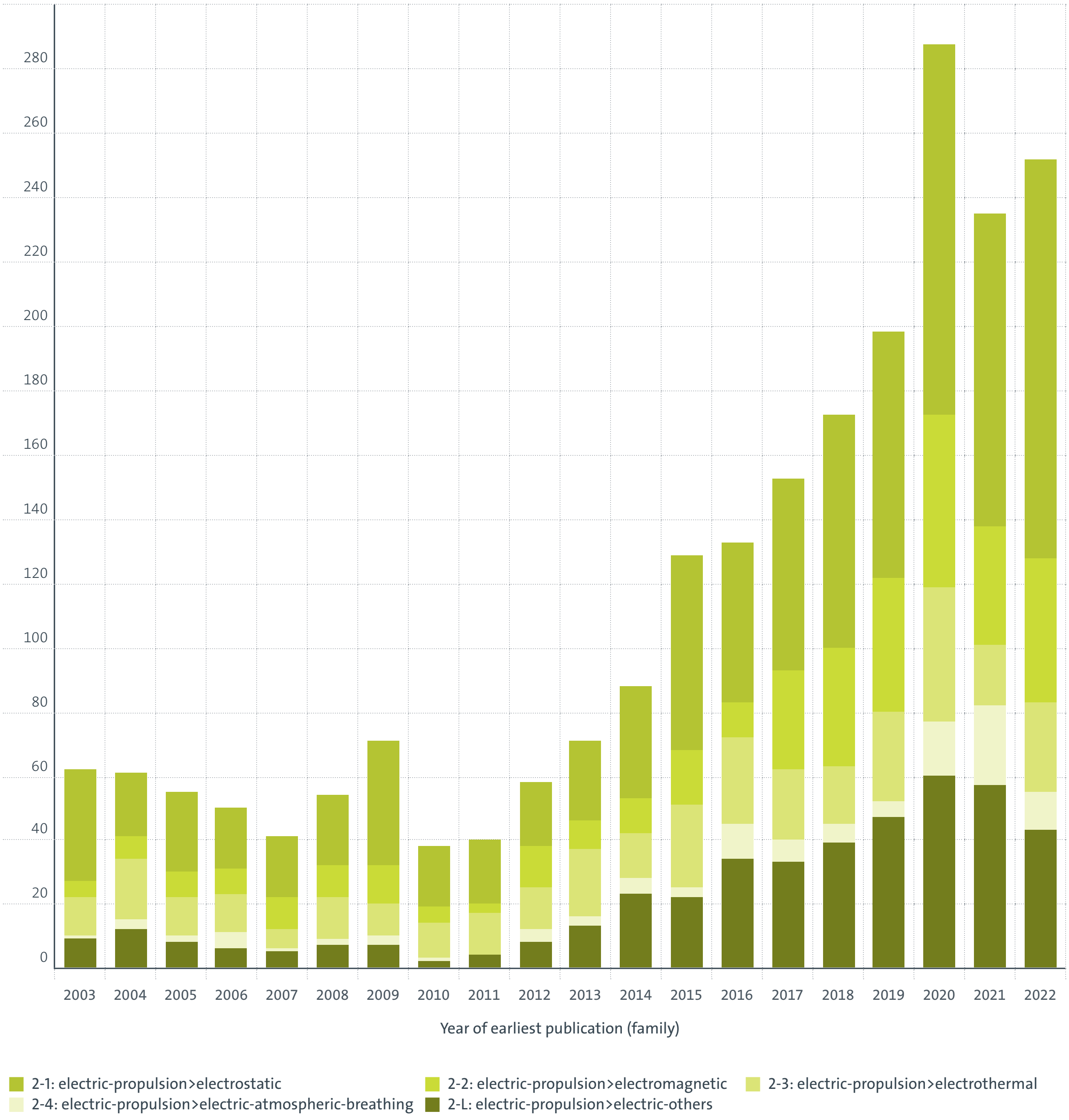


Electric propulsion, historically primarily used for telecommunication satellites in geostationary orbit (GEO), is seen as a critical enabler for many emerging space applications, with LEO telecommunication constellations being the most prominent one. The Starlink constellation of SpaceX alone makes up 67% of the total number of spacecraft launched in 2023[45]. It relies entirely on constant thrust operations using electrostatic propulsion to keep the satellites in orbit despite significant atmospheric drag and also to help the satellites avoid close encounters or collisions with other spacecraft.

[45] ESPI launch database, 2024

Figure 29

Patent filings by electric propulsion concept



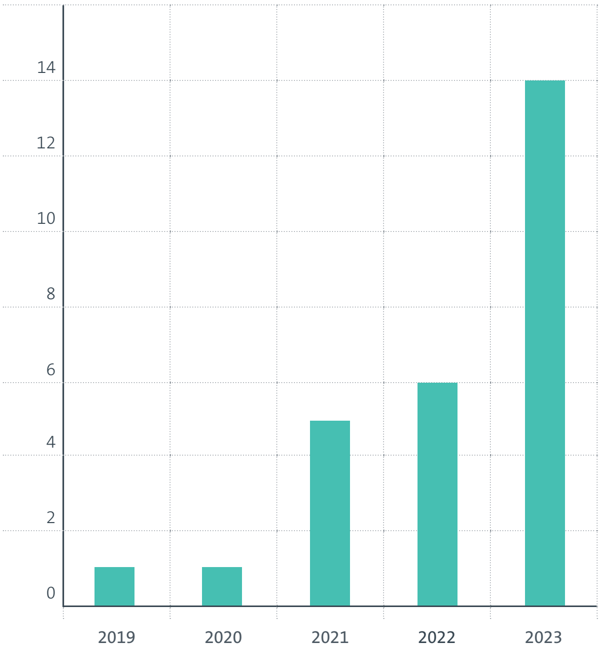
The leading nations, apart from China, are the US, Russia, France, Japan, Germany, United Kingdom and South Korea. On average, patent activity in the field of electric propulsion grew by 10% over the last 20 years. If taken into account, the growth in patents filed in the field of electric propulsion systems would be more modest (3.6%) – driven mainly by US applications which represent 24% of the patent families. Next to the US, China has emerged as the entity filing most patents based on electrostatic propulsion, with a major uptick since 2015. This is in line with the country's plan to set up two commercial telecom constellations in the coming years consisting of 25 000 LEO satellites, which were announced in 2020 and 2023[46].

Another emerging market that electric propulsion enables is on-orbit servicing, assembly, and manufacturing (OSAM) applications. Electric propulsion is used to manoeuvre the OSAM vehicles after they have been initially deployed into space by a launch vehicle (using chemical propulsion). The emergence of OSAM applications has gained traction over the last five years in particular, as shown in Figure 30 (below) for OSAM-specific vehicles launched per year.

Europe plays a significant role in the OSAM market, with the Italian company D-Orbit being the worldwide market leader in last-mile delivery, currently the only OSAM service which is commercially viable[47]. However, Europe's diminished role in the patent landscape for electrostatic propulsion points at OSAM not being the main driver of patents in this field but rather the afore-mentioned large LEO telecom constellations. Beyond constellations and OSAM, electrostatic propulsion could also be used to move space station modules, such as the Lunar Gateway, to their destination.

Figure 30

OSAM vehicles launched per year
(ESPI launch database, 2024)



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[46] https://accesspartnership.com/access-alert-china-announces-plans-for-a-second-mega-constellation-status-of-its-first-system-remains-unknown/

[47] On-orbit Servicing, Assembly, and Manufacturing. ESPI 2023. https://www.espi.or.at/wp-content/uploads/2023/10/Final-Report-OSAM-1.pdf

2.2.4. Alternative propulsion concepts

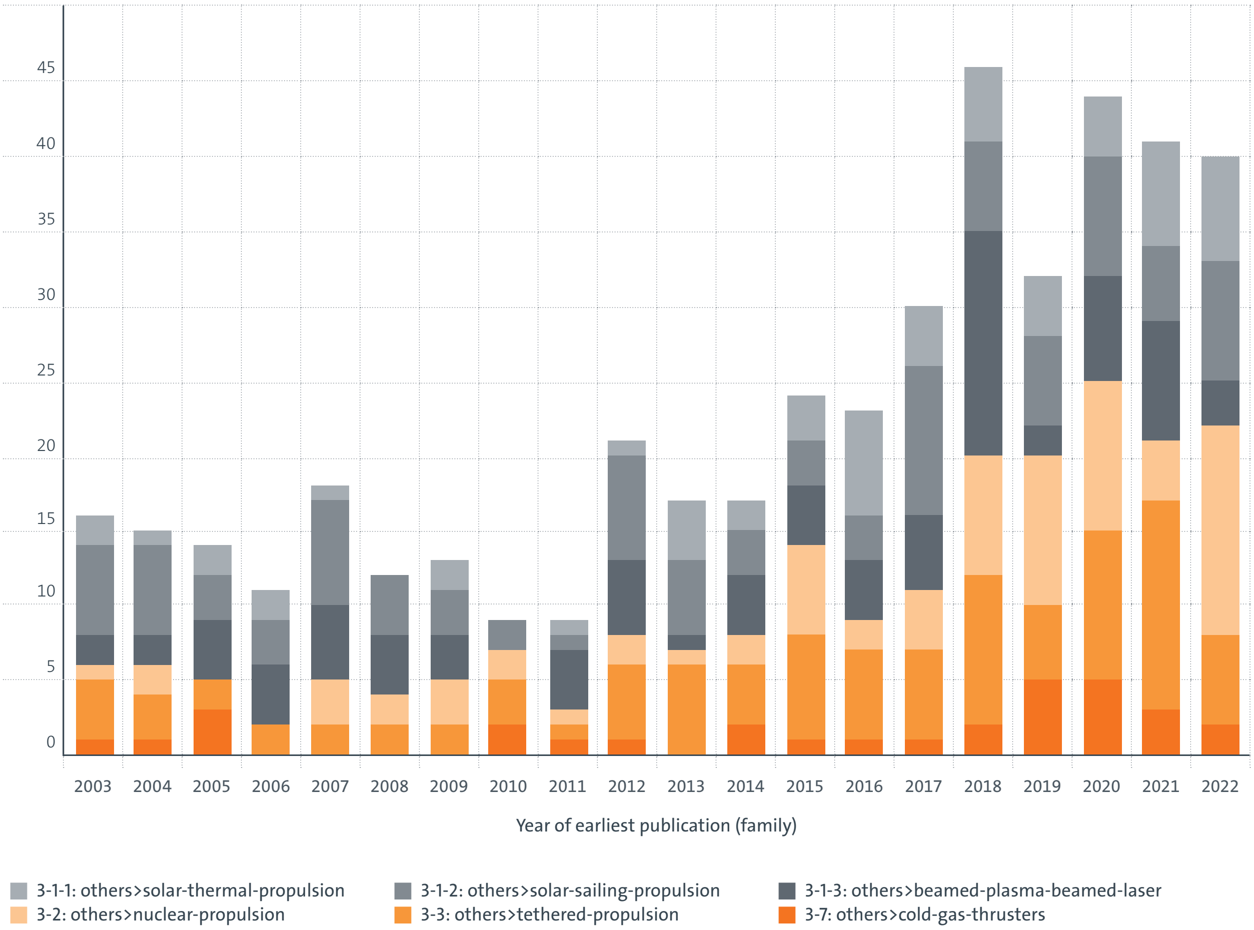
Apart from electric and chemical propulsion, which represent the lion's share of propulsion-related patents propulsion, there are also a few more experimental propulsion concepts such as nuclear, solar sails, beamed energy propulsion or tethered propulsion. The total number of patent filings remains low, but within these domains it has been possible to observe an increase in patent filings classified as nuclear propulsion and beamed energy propulsion over recent years. Figure 31 provides an overview of the major alternative propulsion concepts.

Nuclear propulsion

As for the other more niche propulsion concepts mentioned above, the total number of filings for nuclear propulsion is very low compared to electric or chemical propulsion. However, nuclear propulsion in space is a topic of political significance both within the UN and also the US administration. The total number of patents in this field is rapidly increasing, especially due to filings from US applicants but also because of Chinese filings, which managed to surpass the number of US filings for nuclear propulsion in 2022.

Figure 31

Patent filings for alternative propulsion concepts



As mentioned above, nuclear propulsion (and nuclear energy) is of interest for space exploration and space science missions to more distant objects and celestial bodies[48]. Therefore, the patent data presented in Figure 32, especially for 2022, reflects the current exploration endeavours that are mostly concentrated around both superpowers.[49]

Russia is almost non-existent in patent filings for nuclear propulsion. It filed its last nuclear propulsion patent in 2010. For nuclear propulsion this finding is especially significant because the Russian Federation has a long-standing legacy both in this field and space exploration in general, and it is very active in UN-level discussions concerning the topic.

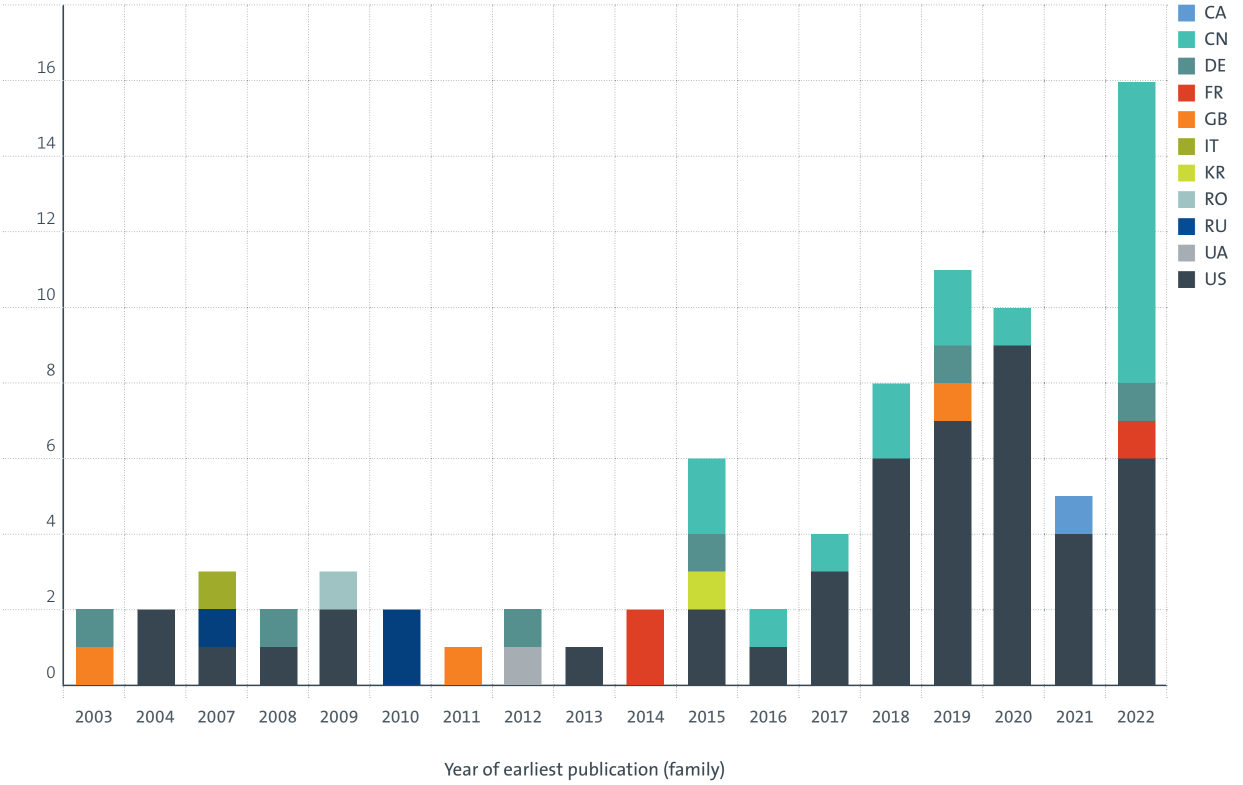
Like Russia, Europe has almost no presence in this field, despite having a history of being a major contributor to exploration efforts led by the US and being one of the most capable players in the field of space science.

Beamed energy propulsion

After nuclear propulsion, beamed energy propulsion is the next most significant in the dataset. It includes sub-concepts such as beamed plasma/laser energy, solar sailing and solar-thermal propulsion used to accelerate spacecraft. While the main application of solar sailing is in long duration flights for exploration or science missions, plasma/laser applications could form a significant part of future endeavours associated with space sustainability. Directed laser beams could be an

Figure 32

Nuclear propulsion patent families by country



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[48] https://www.globalspaceexploration.org/wordpress/wp-content/isecg/NPP_GAT_report_July%2027%202023a.pdf

[49] This is maybe most pronounced when looking at the current plans for lunar exploration. Currently states are bandwagoning behind either the US-led Artemis missions and the related set of governing rules, the Artemis Accords, or behind China's International Lunar Research Station (ILRS).

effective tool for active debris removal. Beams from earth or space could project small energy amounts at space debris, thereby destroying the debris. Similarly, a potential application for this propulsion concept could be in emergency collision avoidance. A spacecraft that has run out of fuel and is on a collision course with another spacecraft could receive a laser beam, which would provide it with enough energy to quickly alter its orbit and avoid a potential collision. It has to be noted though, that the technical realisation of these concepts and the filing numbers for any of the alternative space propulsion sub-concepts (solar-sail, solar-thermal, plasma) are too low for it to be possible to derive any meaningful trends at this stage.

However, alternative propulsion concepts have been the subject of increased interest over recent years and potentially breakthrough research has investigated new technologies, e.g. through the European Space Agency's cross-cutting initiative on 'innovative propulsion'.[50]

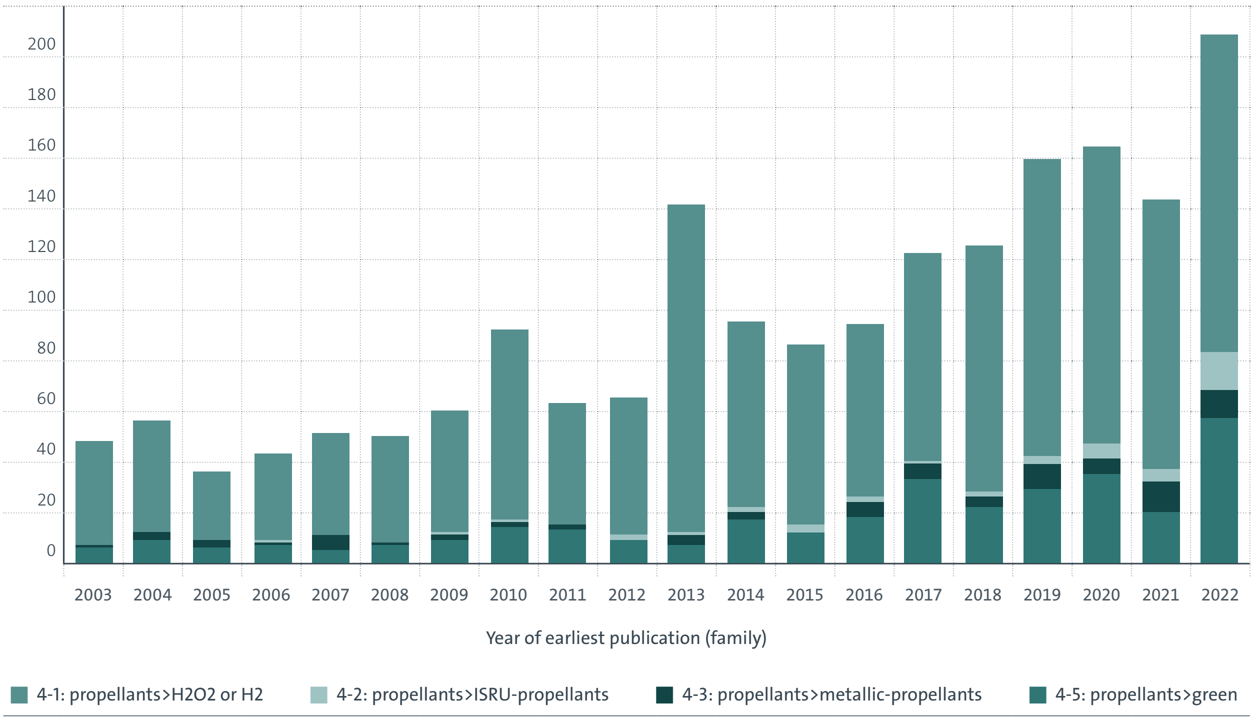
2.2.5. Propellants

Apart from different propulsion techniques this reports also investigates certain propellant concepts and their corresponding patent applications[51]. It must be noted that – as mentioned in section 1.2 – numerous combinations and blends of fuels, oxidisers and resulting propellants exist. While some patenting activity is evident from the dataset, the search queries used to identify applicable patent documents cannot distinguish between individual mixtures or a use in e.g. monopropellant or bipropellant sub-concepts. Thus, the queries target the investigation of four characteristics for propellants:

- Applications for hydrogen-based propellants, including classical H2 and H2O2 but also H2 obtained by electrolysis, e.g. for water propulsion concepts,
- Applications mentioning "in-situ resource utilisation" in combination with propellants,

Figure 33

Propellant concepts over time



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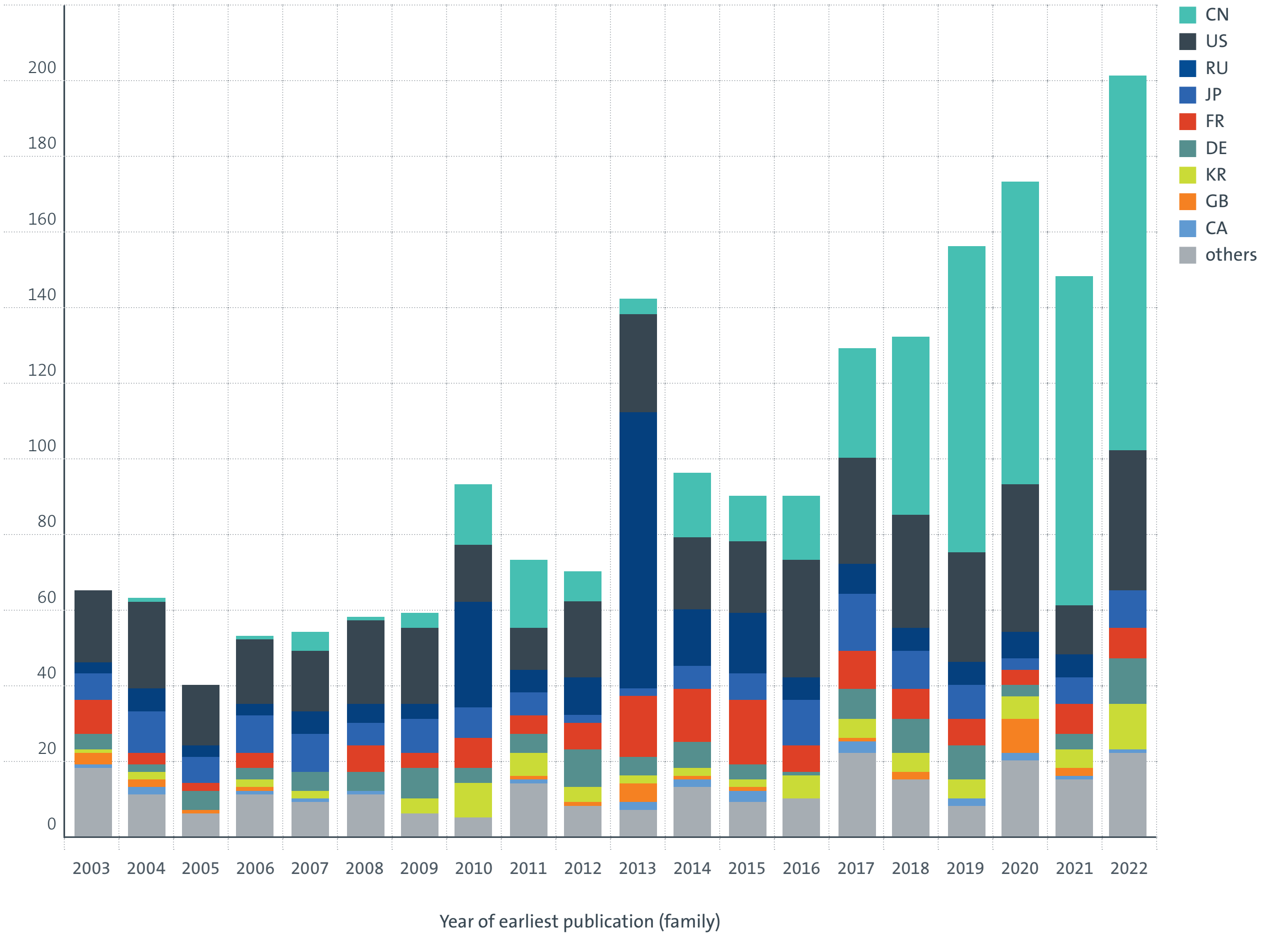
[50] European Space Agency, Cross-Cutting Initiative Innovative Propulsion, https://technology.esa.int/program/innovative-propulsion

[51] It has to be taken into account that for this, as well as for other sections of this report, it is not just granted patents that are considered as part of the analysis.

Figure 34

Propellant applicant countries



– Submissions mentioning the use of metallic propellants, e.g. the use of metallic powders and additives,
– Applications relevant to the notion of "green" propellants, including keywords for non-toxic, eco-friendly, non-polluting and non-hazardous inventions.

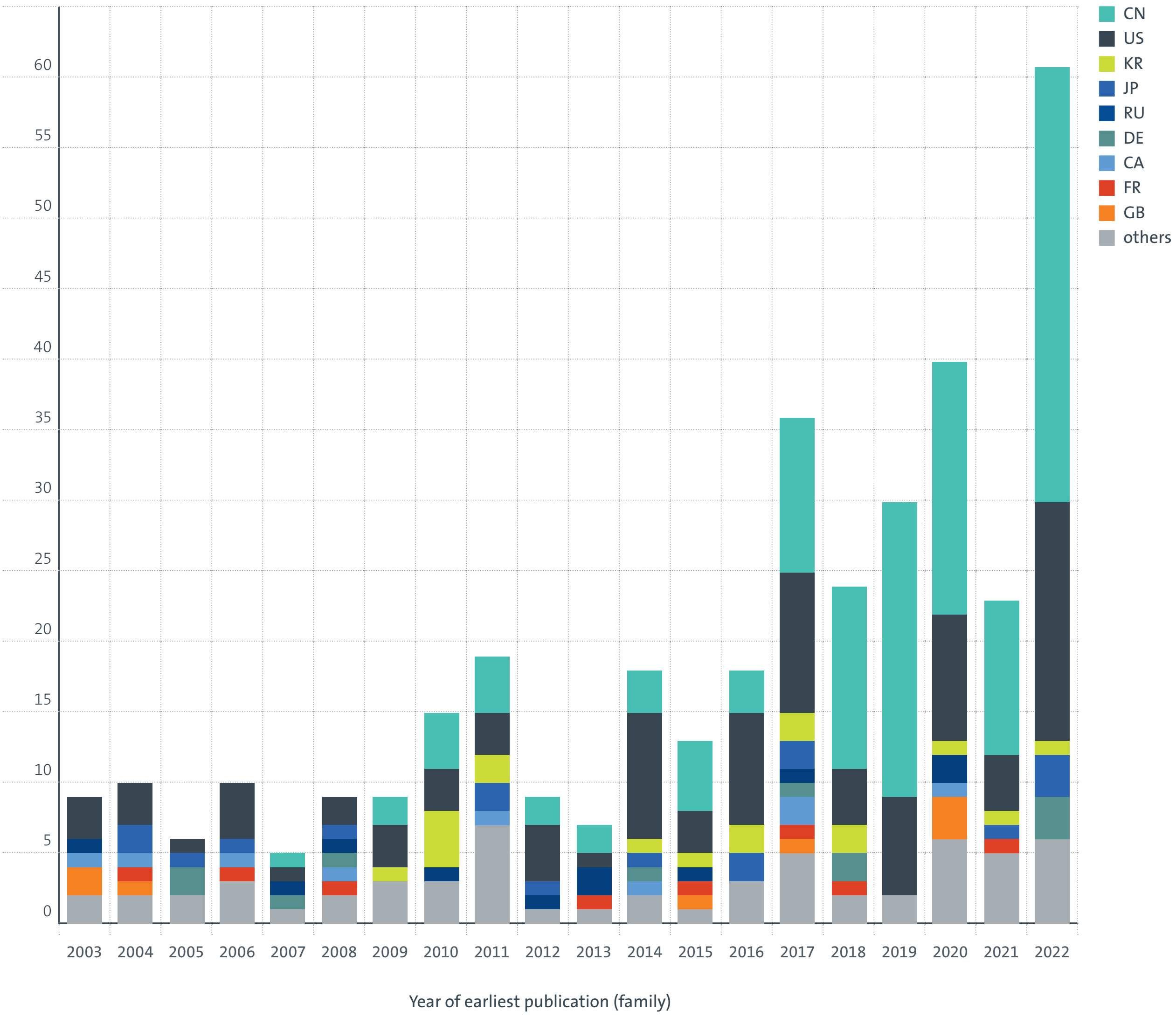
Over recent years, all concepts of patent families regarding propellants have increased over time, but the trend has been most pronounced in hydrogen and green and water propellants[52]. Liquid hydrogen is the most significant propellant concept in the dataset, accounting for more patents than all other propellant concepts combined. Figure 33 shows developments in hydrogen propellants, revealing a significant increase, in line with the overall trends in propulsion-system patents. The reader should note that 30% of the green propellants are also tagged as hydrogen or hydrogen peroxide based.

[52] Water propellants refer to hydrogen-H2, hydrogen peroxide and H2 from water.

Green propellants
Worldwide imperatives to transform to a carbon-neutral and more environmental economy also impact the space sector and have caused new ideas for using green transportation methods to arise. One part of this is the development of green propellants. Investigating the evolution in the number of green-propellant-related patents, it can be seen that there has been a general increase since 2003 which has further accelerated since 2021 – growing almost exponentially. Comparing the average growth in patents from 2003-2022 in respect of green propellants (on average 12.6% per year) with the overall growth of patent applications in the field of propulsion (on average 10.1% per year), it is apparent that that there is indeed a growing interest in green solutions in the propulsion sector albeit still at a low level. Looking at the distribution of applicant countries in Figure 35, it can be seen that China is in a dominating position and that this has accelerated in recent years. The US is in second place. Despite Europe's efforts to be at the forefront of climate protection and green policies through the EUs Green Deal, the number of relevant patent families originating from the continent is of marginal significance.

Figure 35

Green propellant patent filing by country



3. Conclusion

Space propulsion encompasses different principles, most prominently chemical and electric propulsion concepts as well as alternative and emerging concepts accompanied by a variety of propellants and even "fuel-less" concepts, such as solar sails and ABEP. It is a fundamental enabler of a diverse set of space applications, ranging from launch vehicles and on-board propulsion, collision avoidance and on-orbit servicing, assembly, and manufacturing (OSAM), and space exploration endeavours or deep space science probes.

The analysis of propulsion patent data has uncovered some major trends within the innovation landscape surrounding the technology:

1. Globally, space propulsion systems have witnessed a significant increase in patent activity over the last 20 years equivalent to an average annual increase of 9%. This increase has been especially prominent since 2011.

2. International patent activity is primarily concentrated in larger countries or regions which also reflect the traditional players dominating the space sector. This encompasses the US, Europe (primarily France and Germany), Japan, China and Russia.

3. As apparent in other technological domains within and outside the space sector, the strong position of China can be observed in relation to all parts of propulsion systems, which is driving the overall increase in patent filings. This is especially true when considering national and international patent filings.

4. Over the last 20 years European applicants have accounted for 37% of internationally filed patent families. There is however an absolute and relative slowdown of propulsion system development in Europe, in line with the continent's stagnant position in other high-tech sectors.

5. Most patent filings by European countries originate from countries with a heritage in upstream activities, namely France and Germany.

6. Patent activity within the area of chemical propulsion is dominated by the countries that are responsible for the highest level of launch activity and countries of launch service providers.

7. Electric propulsion filings have witnessed the largest increase over the last 20 years, especially in China, and have surpassed chemical propulsion filings in recent years.

8. Nuclear propulsion, albeit still a niche concept, is witnessing increased numbers of filings, with the US and China being the dominant players, which closely resembles their dominance in space exploration, one of the major application areas for this propulsion concept.

9. Currently, despite Europe's efforts to be at the forefront of climate protection and green policies through the EUs Green Deal, the number of relevant patent families about green propellants originating from the continent is of marginal significance.

Limits of the study

This study provides a specific snapshot of a particular technology segment. The approach used could serve as an example of how to exploit patent filing statistics for analyses to deliver insights and information to assist decision-making in both the private and public sectors. This study makes best use of the EPO's publicly available data, search and other analysis tools. Like many patent analyses, this study is based on search queries combining keywords and patent classification codes. These queries are designed to optimise recall (i.e. to retrieve as many relevant documents as possible) and to optimise precision (i.e. to exclude as many non-relevant documents as possible). In reality, for a large dataset it is impossible to obtain 100% recall and 100% precision simultaneously. This affects which documents we found, as did the need to use a number of disparate classification codes in the search. For this report we limited our data sample to the period from the earliest publication year, 2001, up to 2022 to recover all relevant propulsion technologies. We then manually checked a considerable number of patent families to improve precision and recall. However, as a result of the above parameters, "noise" in the dataset is inevitable and some relevant documents may have been missed. Nevertheless, we are confident of our methodology and assumptions. The European Patent Organisation, the European Space Policy Institute and the European Space Agency cannot be held liable for any damages, cost, losses or third-party claims resulting from reliance on the data, information, findings, conclusions and interpretations presented in this report.[53]

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[53] Space propulsion technology is typically classified using IPC & CPC codes B64G1/40 and F03H1/00

Glossary and notes

ABEP	Air Breathing Electric Propulsion systems are defined by their capability to generate thrust using as propellant the gases of the atmosphere, which are collected by an intake installed on the same platform.
Applicant	A person (natural person) or an organisation (i.e. legal entity, company) that has filed a patent application. A patent application may be filed by more than one applicant (joint applicants).
Ansera	Internal EPO tool used by patent examiner to allow easy searches across documents.
Bipropellant	Propellant comprising two (usually liquid) components, a fuel and an oxidiser, which are stored in separate tanks and are injected and mixed inside a combustion chamber.
Citations (in a patent)	Backward citations (back in time): mainly used to describe a reference within a patent search report that documents the prior art relevant to the claims. Forward citations: forward in time seen from the perspective of the cited document; generally accepted as a proxy for patent value.
Co-applicant	One of the joint applicants (see "Applicant").
COPUOS	United Nations Committee on the Peaceful Uses of Outer Space, with the mandate to foster international cooperation on the peaceful uses of outer space, as well as to consider legal issues arising from the exploration of outer space.
EPC (European Patent Convention)	Multilateral international treaty instituting the European Patent Organisation and setting out the rules for the granting of European patents. The EPC contracting states are those countries that are members of the European Patent Organisation. The mission of the European Patent Organisation is to grant European patents in accordance with the EPC.
EPO, European Patent Office	The European Patent Office is the organ of the European Patent Organisation that examines patent applications and grants European patents in accordance with the EPC. European patents may be granted for all EPC contracting states and may be effective in several non-contracting states (validation and extension states).
ESA	The European Space Agency (ESA) is an international organisation with 22 Member States. Its mission is to shape the development of Europe's space capability and ensure that investment in space continues to deliver benefits to the citizens of Europe and the world.
Espacenet	Free service from the EPO for searching patents and patent applications. It includes more than 150 million documents.
ESPI	European Space Policy Institute – Europe's independent think-tank for space. The purpose of ESPI is to promote European space policy at a global level; develop approaches to European space policy and provide an active forum for the analysis and discussion of European needs, capabilities, and long-term prospects in space activities.
GIE	Gridded ion engines produce thrust by accelerating a beam of ions using electric fields. GIEs consist of three basic components: the ion generator, the ion accelerator and the neutraliser.
GOCE	The title page of this report shows ESA's Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite, launched on 17 March 2009. ESA's Earth Explorer GOCE mission was to map the Earth's gravity with unrivalled precision and it provided the most accurate model of the 'geoid' ever produced.
Green propellants	Patents that have been identified via a dedicated search strategy and which claim environmentally friendly, clean or non-toxic attributes to the propellant invention. Full label = '4-5: propellants>green' in the data.

IAEA	International Atomic Energy Agency
International patent family (IPF)	Patents that have more than one country in the list of publications, applicants, inventors or first priority countries. Using this concept allows identification (and exclusion) of single national filings that have no family members in other patent jurisdictions. Patents filed at the EPO, WIPO and other regional patent organisations are IPF patents by default.
Invention	Teaching of a technical device, method or use which is new, non-obvious and may be applied in industry, including agriculture.
Inventor	A person designated as an inventor in a patent application. An inventor can also be an applicant. An inventor is always a natural person. There may be more than one inventor per application.
ISRU propellant	Propellant based on in-situ resource utilisation
LEO	A low Earth orbit (LEO) is an orbit that is relatively close to the Earth's surface. It is normally at an altitude of less than 1000 km but could be as low as 160 km above Earth.
LH2	Liquid hydrogen
LOX	Liquid oxygen
MEMS	Micro-electro-mechanical systems
MMH	Monomethylhydrazine
OSAM	On-orbit servicing, assembly and manufacturing
Patent application	Document describing the invention for which patent protection is sought. It consists of the claims which define the scope of the invention, the description which explains the invention and (optionally) drawings which illustrate the invention.
Patent authority	The patent office where a patent was filed. Normally represented using a WIPO STANDARD ST.3 code: wipo.int/export/sites/www/standards/en/pdf/03-03-01.pdf.
Patent classification	CPC or IPC classifications: classification scheme or system of codes that groups inventions according to technical area. Often used in patent analytics to create uniform patent samples.
Patent family	A set of patent documents covering the same or similar technical content, depending on the patent family definition. The size of the patent family refers to the number of patent applications in the family.
PATSTAT	The EPO's PATSTAT database has become a point of reference in the field of patent intelligence and statistics. It helps users perform sophisticated statistical analyses of bibliographical and legal event patent data.
Priority filing	The earliest patent application of a family from which subsequent applications of that family claim priority. The priority date is the date on which the earliest application (priority application) was filed.
STM (Space Traffic Management)	According to the European Union, "STM encompasses the means and the rules to access, conduct activities in, and return from outer space safely, sustainably, and securely"
UDMH	Unsymmetrical dimethylhydrazine

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Citation

EPO, ESPI and ESA (2024), Patent insight report: Propulsion systems for space, EPO, Vienna

Cover image

ESA's Gravity field and steady-state Ocean Circulation Explorer (GOCE).
The cover image of this report shows ESA's GOCE satellite, launched on 17 March 2009. The GOCE mission managed to overcome the small amount of drag still present in space by means of an electric ion propulsion system mounted at the back of the satellite. Although its flight is now over, the wealth of data from GOCE continues to be exploited to improve our understanding of ocean circulation, sea level, ice dynamics, climate change and the Earth's interior. © ESA/AOES Medialab

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This report is published and edited by the
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Acknowledgements
Nuria Hernandez Alfageme (ATG Europe on behalf of ESA)
Victor Fernandez Villace (ESA)
Jamila Mansouri (ESA)
Armin Herbertz (ESA)
Nicolas Arcis (ESA)
Davina Maria Di Cara (ESA)
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Design
European Patent Office

ISBN 978-3-89605-377-0