ASPI's two-decade Critical Technology Tracker:

The rewards of long-term research investment

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Governments and organisations interested in supporting this ongoing program of work, including further expansions and the addition of technologies, can get in touch via: criticaltech@aspi.org.au.

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Executive summary

This report accompanies a major update of ASPI's *Critical Technology Tracker* website,[1] which reveals the countries and institutions—universities, national labs, companies and government agencies—leading scientific and research innovation in critical technologies. It does that by focusing on high-impact research—the top 10% of the most highly cited papers—as a leading indicator of a country's research performance, strategic intent and potential future science and technology (S&T) capability.

Now covering 64 critical technologies and crucial fields spanning defence, space, energy, the environment, artificial intelligence (AI), biotechnology, robotics, cyber, computing, advanced materials and key quantum technology areas, the *Tech Tracker's* dataset has been expanded and updated from five years of data (previously, 2018–2022)[2] to 21 years of data (2003–2023).[3]

These new results reveal the stunning shift in research leadership over the past two decades towards large economies in the Indo-Pacific, led by China's exceptional gains. The US led in 60 of 64 technologies in the five years from 2003 to 2007, but in the most recent five years (2019–2023) is leading in seven. China led in just three of 64 technologies in 2003–2007[4] but is now the lead country in 57 of 64 technologies in 2019–2023, increasing its lead from our rankings last year (2018–2022), where it was leading in 52 technologies.

India is also emerging as a key centre of global research innovation and excellence, establishing its position as an S&T power. That said, the US, the UK and a range of countries from Europe, Northeast Asia and the Middle East have maintained hard-won strengths in high-impact research in some key technology areas, despite the accelerated efforts of emerging S&T powers.

This report examines short- and long-term trends, to generate unique insights. We have updated the recent five-year results (2019–2023) to show current research performance rankings (top 5 country results are in Appendix 1). We have also analysed our new historical dataset to understand the country and institutional trends in research performance over the full 21-year period. In select technologies we have also made projections, based on current trends, for China and the US to 2030.

The results show the points in time at which countries have gained, lost or are at risk of losing their global edge in scientific research and innovation. The historical data provides a new layer of depth and context, revealing the performance trajectory different countries have taken, where the momentum lies and also where longer term dominance over the full two decades might reflect foundational expertise and capabilities that carry forward even when that leader has been edged out more recently by other countries. The results also help to shed light on the countries, and many of the institutions, from which we're likely to see future innovations and breakthroughs emerge.

China's new gains have occurred in *quantum sensors*, *high-performance computing*, *gravitational sensors*, *space launch* and *advanced integrated circuit design and fabrication* (semiconductor chip making). The US leads in *quantum computing*, *vaccines and medical countermeasures*, *nuclear medicine and radiotherapy*, *small satellites*, *atomic clocks*, *genetic engineering* and *natural language processing*.

India now ranks in the top 5 countries for 45 of 64 technologies (an increase from 37 last year) and has displaced the US as the second-ranked country in two new technologies (*biological manufacturing* and *distributed ledgers*) to rank second in seven of 64 technologies. Another notable change involves the UK, which has dropped out of the top 5 country rankings in eight technologies, declining from 44 last year to 36 now.

Besides India and the UK, the performance of most secondary S&T research powers (those countries ranked behind China and the US) in the top 5 rankings is largely unchanged: Germany (27), South Korea (24), Italy (15), Iran (8), Japan (8) and Australia (7).

We have continued to measure the risk of countries holding a monopoly in research for some critical technologies, based on the share of high-impact research output and the number of leading institutions the dominant country has. The number of technologies classified as 'high risk' has jumped from 14 technologies last year to 24 now. China is the lead country in every one of the technologies newly classified as high risk—putting a total of 24 of 64 technologies at high risk of a Chinese monopoly. Worryingly, the technologies newly classified as high risk includes many with defence applications, such as *radar, advanced aircraft engines*, *drones, swarming and collaborative robots* and *satellite positioning and navigation*.

In terms of institutions, US technology companies, including Google, IBM, Microsoft and Meta, have leading or strong positions in artificial intelligence (AI), quantum and computing technologies. Key government agencies and national labs also perform well, including the National Aeronautics and Space Administration (NASA), which excels in space and satellite technologies. The results also show that the Chinese Academy of Sciences (CAS)—thought to be the world's largest S&T institution[5]—is by far the world's highest performing institution in the *Critical Tech Tracker*, with a global lead in 31 of 64 technologies (an increase from 29 last year, see more on CAS in the breakout box on page 19).

The results in this report should serve as a reminder to governments around the world that gaining and maintaining scientific and research excellence isn't a tap that can be turned on and off. Too often, countries have slowed or stopped investing in, for example, research and development (R&D) and manufacturing capability, in areas in which they had a long-term competitive advantage (5G technologies are an example[6]). In a range of essential sectors, democratic nations risk losing hard-won, long-term advantages in cutting-edge science and research—the crucial ingredient that underpins much of the development and advancement of the world's most important technologies. There's also a risk that retreats in some areas could mean that democratic nations aren't well positioned to take advantage of new and emerging technologies, including those that don't exist yet.

Meanwhile, the longitudinal results in the *Critical Tech Tracker* enable us to see how China's enormous investments and decades of strategic planning are now paying off.[7]

Building technological capability requires a sustained investment in, and an accumulation of, scientific knowledge, talent and high-performing institutions that can't be acquired through only short-term or *ad hoc* investments.[8] Reactive policies by new governments and the sugar hit of immediate budget savings must be balanced against the cost of losing the advantage gained from decades of investment and strategic planning. While China continues to extend its lead, it's important for other states to take stock of their historical, combined and complementary strengths in all key critical technology areas.

This report is made up of several sections. Below you'll find a summary of the key country and institutional findings followed by an explanation of why tracking historical research performance matters. We then further analyse the nuances of China's lead and briefly explain our methodology (see Appendix 2 for a detailed methodology). We also look more closely at 10 critical technology areas, including those relevant to AI, semiconductors, defence, energy, biotechnology and communications. Appendix 1 contains visual snapshots of top 5 country rankings in the 64 critical technologies.

We encourage you to visit ASPI's *Critical Technology Tracker* website (https://techtracker.aspi.org.au) and explore the new data.

What is ASPI's *Critical Technology Tracker?*

ASPI's *Critical Technology Tracker* is a unique dataset that allows users to track 64 technologies that are foundational for our economies, societies, national security, defence, energy production, health and climate security. It focuses on the top 10% of the most highly cited research publications from the past 21 years (2003–2023).[9] The new dataset is analysed to generate insights into which countries and institutions—universities, national labs, companies and government agencies—are publishing the greatest share of innovative and high-impact research. We use the top 10% because those publications have a higher impact on the full technology life cycle and are more likely to lead to patents, drive future research innovation and underpin technological breakthroughs.[10]

Critical technologies are current or emerging technologies that have the potential to enhance or threaten our societies, economies and national security. Most are dual- or multi-use and have applications in a wide range of sectors. By focusing early in the science and technology (S&T) life cycle, rather than examining technologies already in existence and fielded, the *Critical Technology Tracker* doesn't just provide insights into a country's research performance, but also its strategic intent and potential future S&T capability. It's only one piece of the puzzle, of course: it must be acknowledged that actualising and commercialising research performance into major technological gains, no matter how impressive a breakthrough is, can be a difficult, expensive and complicated process. A range of other inputs are needed, such as an efficient manufacturing base and ambitious policy implementation.

The *Tech Tracker's* dataset has now been expanded and updated from five years of data (previously, 2018–2022)[11] to 21 years of data (2003–2023). This follows previous attempts to benchmark research output across nations by focusing on quality over quantity, key technology areas and individual institutions, as well as short-term, long-term and potential future trends. This update continues ASPI's investment in creating the highest quality dataset of its kind.[12]

Both the website and two associated reports (this one included) provide decision-makers with an empirical methodology to inform policy and investment decisions, including decisions on which countries and institutions they partner with and in what technology areas. A list of the 64 technologies, including definitions, is on our website.[13] Other parts of this project include:

- **the Tech Tracker website:** ASPI's *Critical Technology Tracker*[14] contains an enormous amount of original data analysis. We encourage you to explore these datasets online as you engage with this report. Users can compare countries, regions or groupings (the EU, the Quad, China–Russia etc.) and explore the global flow of research talent for each technology.
- **the 2023 report:** We encourage readers to explore the original report, *ASPI's Critical Technology Tracker: the global race for future power.*[15] In addition to analysing last year's key findings, it outlined why research is vital for S&T advances and it examined China's S&T vision. The report also made 23 policy recommendations, which remain relevant today.[16]
- **visual snapshots:** Readers looking for a summary of the top 5 countries ranked by their past five years of performance in all 64 technologies (see example below) can jump to Appendix 1.

Supercapacitors	9/10 8.1	 62.9%	 7.8%	 6.0%	 3.6%	 1.9%
Advanced aircraft engines	10/10 9.0	 63.1%	 7.0%	 3.6%	 3.0%	 3.0%

Key findings

Global and country findings

- **China's lead continues to grow:** China has strengthened its global research lead in the past year and is currently leading in 57 of 64 critical technologies. This is an increase from 52 technologies last year, and a leap from the 2003–2007 period, when it was leading in just three technologies. Over the past 21 years, China's rise from a mid-tier position in global research in the late 2000s to mid-2010s into a research and science powerhouse today has been gradual but consistent. It's been able to convert its research lead into manufacturing[17] in some fields such as *electric batteries*,[18] though there are other areas in which China has been slower to convert its strong research performance into actual technology capability (see page 16).
- **China significantly strengthened its standing in the middle of the last decade:** It was ahead of the US in 28 technology fields (out of the 64) in the years from 2013 to 2017. In other areas, it has only recently nudged ahead in the 2020s, including in *high-performance computing*, *adversarial AI*, *advanced integrated circuit design and fabrication* (semiconductor chip making), *autonomous systems operation technology* and *quantum sensors*, reflecting Beijing's push into AI and computing. It has also reached parity in its annual publication rate in *natural language processing*.
- **The US is losing the strong historical advantage that it has built:** Over the 21-year period, the US has been unable to hold its research advantage. In the early to mid-2000s, the US was by far the dominant research power. Its performance between 2003 and 2007 saw it leading in research for 60 out of 64 technologies. Over two decades, however, that research lead has slipped to only seven technologies (in the 2019–2023 ranking). Some notable holdouts include *quantum computing* and *vaccine and medical countermeasures*, in which the US still maintains a dominant position.[19] The knowledge, expertise and institutional strengths built over decades of investment and pioneering research are likely to continue to benefit the US in the short term, but China is catching up rapidly through an unsurpassed investment in its own S&T areas and top-performing institutions, especially in key defence and energy technology areas.
- **China has built up potential monopoly positions in scientific expertise and top performing institutions:**[20] In the fields in which China overtook the US a decade or more ago, it has tended to build steady and unassailable leads. In advanced materials and manufacturing, for instance, China made big gains from the late 2000s to mid-2010s, such that it now poses a monopoly risk with extremely high concentrations of research expertise and top-performing institutions in fields including *advanced composite materials*, *advanced protection*, *coatings*, *smart materials*, *novel metamaterials*, and *nanoscale materials and manufacturing*. In several key communication fields, notably *advanced optical* and *radiofrequency communication*, and *undersea wireless communication*, China took the lead in the mid-2010s and has built up substantial leads with between three and five times the research output of the US in the past five years, again posing monopoly threats. In comparison, China's gains have been relatively recent in biotechnology, gene technology and vaccines, enabling it to surpass the US in its annual high-impact publication rate in the second half of the 2010s and into the 2020s in five of the seven biotechnologies covered in the *Tech Tracker* (see Appendix 1 for a visual summary of all 64 technologies). The biotechnology field in which China poses the most significant monopoly risk is *synthetic biology*, where it's publishing nearly five times more high-impact research than the US after taking the lead in 2016. However, the US still leads in *nuclear medicine and radiotherapy* and maintains a substantial lead in *vaccines and medical countermeasures*.
- **India accelerates:** India now ranks in the top 5 countries for 45 of 64 technologies (an increase from 37 last year). This represents enormous gains from 2003–2007, in which India only placed in the top 5 countries for four technologies.[21] While India does not yet lead in any of the 64 critical technologies (note that currently only China and the US lead in

any technology), it's a strong performer across a range of technologies, especially in *biofuels* and *high-specification machining processes*, making major gains since 2019.

- Despite India's upwards trajectory, few Indian institutions appear in the top 5 rankings across any period between 2003–2023. By recent performance, only five Indian institutions place within the top 5 across the 64 technologies.[22] Given that India currently does well at the national level (top 5 in 45 technologies), this finding suggests that the country's research and scientific expertise in critical technologies is highly fragmented. That lack of standout institutional performers may be limiting India's ability to attract foreign research talent and motivate prominent Indian scientists and technologists to stay at, or come back to, Indian institutions. This stands in contrast to a much smaller country such as Singapore, which manages to break into the top 5 country ranking in only two technologies, *supercapacitors* and *novel metamaterials,* but is then equally well represented in the top 5 institution rankings by the Nanyang Technological University (top 5 for 3 technologies) and the National University of Singapore (top 5 for 2).
- India seems poised to overtake China in its publication rate in *biofuels* within the next few years. This is significant and would mark the only technology in which the lead country isn't the US or China.

• **The UK drops:** The UK ranks in the top 5 countries for 36 technologies—a decline from 44 technologies in last year's results. Looking at the 2003 to 2007 snapshot of results, the UK ranked in the top 5 countries for 47 technologies. The technologies in which the UK has fallen out of the top 5 rankings are spread across a range of areas, but are mostly technologies related to advanced materials, sensing and space. For example, the 2003 to 2007 snapshot shows the UK placing 2nd in *satellite positioning and navigation* and *small satellites* and 3rd in *space launch systems*. However, recent performance shows the UK placed 6th, 8th and 9th in these technologies, respectively. There have been some gains as well, particularly in defence related technologies such as *electronic warfare* and *directed energy technologies.*

• **The European Union, as a whole, is a competitive technological player:** With members of the EU aggregated over the past five years, we found that the EU leads in two technologies (*gravitational-force sensors* and *small satellites*) and is ranked second in 30 technologies. When counted as a bloc, the EU's position as the first- or second-ranked 'country' can change the *technology monopoly risk* in those technologies because of its impact on the ratio of the lead country's research share over that of the second-ranked country as well as the number of institutions.

- As a bloc, the EU's stronger alignment on building and supporting S&T capability can be seen through programs like Horizon Europe, the EU's key program that funds research and innovation (worth €93.5 billion in 2021–27),[23] and fellowships which encourage and support the mobility of talent such as the European Commission's Marie Skłodowska-Curie fellowships.[24] Many of the top performing European institutions in the *Tech Tracker* have long benefited (some substantially)[25] from these generous funding schemes. Groupings like AUKUS and the Quad (US, Japan, India, and Australia) could learn a lot from such schemes as they increase investment in select critical technology areas.

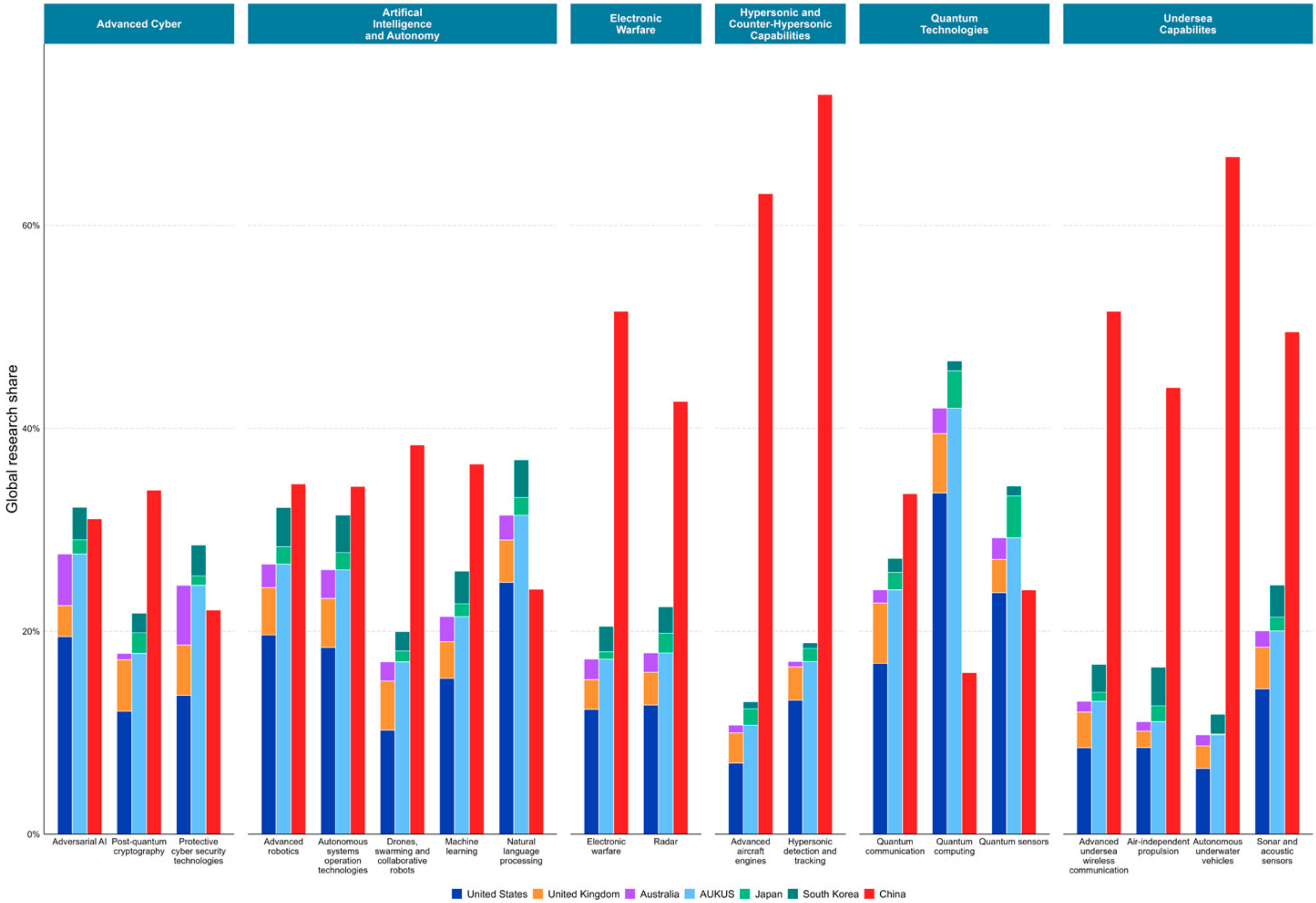
• **Germany is the top-performing European Union country:** Germany ranks in the top 5 countries in 27 technologies in recent results, with Italy in the top 5 in 15 technologies, and France lagging behind, ranking in the top 5 in only three technologies.

- Looking historically at 2003–2007, Germany was also the top-performing country in Europe, placing in the top 5 in 45 technologies compared with France (32) and Italy (10).

• **South Korea's performance shows that Japan has work to do:** South Korea is in the top 5 for an impressive 24 technologies, mostly in the AI and energy and environment categories, while Japan is reduced to only eight, with strengths in *wide and ultrawide bandgap semiconductors* and *nuclear energy.* Looking back to 2003–2007 shows that the two countries, which have similar histories of high-technology industrial strength, have more-or-less inverted in their positions over the two decades, with Japan then ranked in the top 5 countries in 32 technologies compared with South Korea's seven.

- **Iran excels at defence-sensitive technologies:** Based on its performance over the past five years, Iran is in the top 5 countries in eight of the 64 technologies and is strong in advanced materials and manufacturing and biotechnologies. Iran ranks 3rd in *smart materials* and *air independent propulsion.* Back in 2003–2007, Iran's best performance was ranking 17th in *machine learning.*[26]
  - In *air-independent propulsion*,[27] Iran has three of the top 10 institutions: the University of Tehran (5th), Islamic Azad University (7th) and Shahrood University of Technology (9th). In fact, Iran is the only country other than China to have institutions in the top 10 institutions in *air-independent propulsion*, *smart materials* and *advanced data analytics*. Islamic Azad University is the top Iranian institution and makes the top 10 institutions in six other technologies when ranked by recent performance: *mesh and infrastructure-independent networks* (1st), *drones, swarming and collaborative robots* (8th), *smart materials* (7th), *advanced data analytics* (7th), *antibiotics and antivirals* (6th) and *biofuels* (8th).
- **Australia has improved in some technologies and slipped in others:** Based on recent performance, Australia is in the top 5 countries in seven technologies—a small drop from last year, when it ranked in the top 5 in nine technologies (the losses were in *additive manufacturing* and *advanced protection*).
  - When comparing Australia's recent results with those of 2003–2007, Australia has improved its overall ranking by moving up to rank in the top 10 countries in AI and robotic technologies (*machine learning*, *natural language processing*, *advanced robotics* and *autonomous systems operation technologies*), advanced materials and manufacturing (*critical minerals extraction and processing* and *nanoscale materials and manufacturing*), energy and environment (*hydrogen and ammonia for power* and *supercapacitors*) and biotechnologies (*synthetic biology* and *genetic engineering*).
  - But Australia has slipped significantly in all quantum *technologies* except for *quantum sensors*, *biological manufacturing* and in some key defence technologies (*autonomous underwater vehicles*, *satellite positioning and navigation* and *hypersonic detection and tracking*).
- **AUKUS—the trilateral security and technology partnership involving the US, the UK and Australia[28]—closes the gap in some Pillar 2–relevant technologies, but not all:** In a few technologies, such as *adversarial AI*, the combined research efforts of the AUKUS countries place the grouping on par with China (as the lead country). But, in a range of technologies, such as *advanced robotics* and *autonomous systems operation technology*, combined AUKUS efforts still trail China's high-impact research output (see Figure 1 below).
  - Combining AUKUS efforts with those of closer partners Japan and South Korea in these areas however helps close the gap in research performance. In some technologies, such as *autonomous underwater vehicles* and *hypersonic detecting and tracking*, China's high-impact research lead is so pronounced that no combination of other countries can currently match it.
  - However, for all countries, it's important to note that research underpinning the development of defence-related technologies can be considered sensitive and is among the most likely to shift into classified and commercial-in-confidence labs and projects. As the US has peaked earlier than China in those research areas, for example, it's possible that, in some sensitive technology areas, there has been a movement of some research into classified or commercial-in-confidence spaces that has occurred after some of those peaks (for more discussion on this see pages 15-18). Notwithstanding that caveat, countries should avoid complacency, given that China, and all countries, are likely to do the same.

Figure 1: Research share across a range of AUKUS Pillar 2–relevant technologies



Data source: ASPI Critical Technology Tracker

Technology monopoly risk metric results

- **Scientific breakthroughs and research innovations in key defence technologies are increasingly likely to occur in China:** Our technology monopoly risk metric—which show where there have been high concentrations of scientific expertise and high-impact research output in a single country within the past five years—reveals that various technologies with clear military and national-security applications have now changed from medium to high.[29] The new critical technologies now classified as 'high-risk' include *radar*, *satellite positioning and navigation*, *advanced aircraft engines*, and *drones, swarming and collaborative robots*. They join *hypersonic detection and tracking* and *electronic warfare*.
- **China's research lead in advanced materials and manufacturing technologies grows:** China has steadily increased its research dominance in advanced materials and manufacturing—a category in which it already had a substantial lead.[30] Three additional technologies (*high-specification machining processes*, *novel metamaterials* and *smart materials*) have now increased from medium to high risk (see Appendix 1). *Advanced protection* has increased from low to high risk, while two other technologies (*advanced magnets and superconductors* and *continuous-flow chemical synthesis*) have increased from low to medium risk.

Institutional findings: US tech companies, government agencies and CAS

- **Private-sector research is increasingly concentrated in US technology giants:** Looking at high-impact research conducted between 2019 and 2023, we see research excellence consolidating within a few US technology giants. IBM now ranks 1st in *quantum computing*, Google ranks 1st in *natural language processing* and 4th in *quantum computing*, and Meta and Microsoft also place 7th and 8th in *natural language processing* respectively. The only non-US based companies that rank in the top 20 institutions for any technology are the UK division of Toshiba, which places 13th in *quantum communications*, and Taiwan Semiconductor Manufacturing Company Limited (TSMC), which place 20th in *advanced integrated circuit design and fabrication*.
  - **Private sector research was more diverse between 2003-2007:** When we look back at results from the 2003–2007 snapshot, there were a range of companies from around the world that ranked in the top 20 institutions. To name a few, IBM (US) ranked 1st in *high-performance computing*, Philips (Netherlands) ranked 3rd in *advanced integrated circuit design and fabrication*, Samsung (South Korea) ranked 5th in *advanced radiofrequency communications*, Microsoft (US) tied for 6th in *natural language processing*, Nokia[31] (US) and Nippon Telegraph and Telephone (NTT, Japan) ranked 4th and 7th respectively in *advanced optical communications*, Reaction Engines Limited (UK) ranked 3rd in *space launch systems*, and Merck (US) ranked 8th in *novel antibiotics and antivirals* research. Also placing in the top 20 rankings in different critical technology areas were Texas Instruments, Siemens and General Electric.
- **The Chinese Academy of Sciences (CAS) is the global science and research powerhouse:** CAS, which is thought to be the world's largest research institute, is the top-performing institution in the *Critical Technology Tracker*. With approximately 113 institutes, its sheer size propels it into a dominant position.[32] For research conducted in the past five years, CAS leads, against all other institutions, in 31 of 64 technologies—a major increase from 2003–2007, when CAS was leading in only six technologies. CAS currently excels in energy and environment technologies, advanced materials (including *critical minerals extraction and processing*) and in a range of quantum, defence and AI technologies, including *advanced data analytics*, *machine learning*, *quantum sensors*, *advanced robotics* and *small satellites* (see page 19 for more on CAS).
- **Government agencies and national laboratories feature prominently:** A range of government-affiliated research organisations appear throughout the 2019–2023 rankings. In particular, NASA ranks 1st in *space launch systems* and 3rd in *small satellites*, and the US's National Institute of Standards and Technology ranks 2nd in *atomic clocks.* After CAS (discussed above), the government-affiliated organisation that ranks strongly across the most technologies is

the Helmholtz Association of German Research Centres, which ranks 2nd in *space launch systems*, 3rd in *satellite positioning and navigation*, 4th in *advanced magnets and superconductors* and 5th in gravitational sensors.[33]

- However, the presence of government agencies and labs has dropped over the 21-year period. There were many more in the 2003–2007 data, and they were leading in more technologies. For example, in 2003–2007 the French National Centre for Scientific Research led in *advanced magnets and superconductors*, *small satellites* and *supercapacitors*, India's Council of Scientific and Industrial Research led in *biological manufacturing*, and the US's Agricultural Research Service led in *biofuels.* The direct involvement of government-affiliated research organisations is especially evident in technologies with strong defence applications such as *advanced explosives and energetic materials*, where each of the top 3 institutions were government-affiliated: the Los Alamos National Laboratory (US), the Defence Research and Development Organisation (India) and the Russian Academy of Sciences. Our results show that a similar concentration of government-linked research institutes was leading in *advanced aircraft engines* in 2003–2007.

- **Chinese companies play a relatively small role in the global research ecosystem:** Despite their very strong performance in a wide range of technologies at the national level, Chinese companies still lag in their rankings for high-impact research. For example, in *advanced aircraft engines*, a technology for which China published around 70% of total global high-impact research in 2023, the top-performing company is the Aero Engine Corporation of China (founded in 2016), which on recent performance ranks 22nd. Similarly, in *advanced radiofrequency communication*, in which China was responsible for 30% of global high-impact research in 2023, Huawei Technologies, as the top-performing Chinese company, ranks only 58th by recent performance and is completely absent when ranked by performance between 2003 and 2007. While for all countries it's research-dedicated institutions that lead most of the rankings in the *Tech Tracker*, it's surprising that Chinese companies aren't higher up and closer to their US counterparts, many of which rank highly.

Methodology in brief

The Critical Technology Tracker looks at technological development and innovation through the prism of high-impact research performance, noting that the links between high-quality research and scientific and technological advances are well known.[34] In this update of the *Critical Technology Tracker*, we analyse the top 10% most highly cited research publications in 64 critical technologies over a 21-year period. We analyse recent results and those from the past (for example, 2003–2007) to gain greater insights into how the research performance of countries and institutions has evolved and changed over time, and, at times, their potential future trajectory. We use the top 10% because those publications have a higher impact on the full technology life cycle and are more likely to lead to patents, drive future research innovation and underpin technological breakthroughs.[35] A full and detailed methodology is in Appendix 2.

Updating the *Critical Technology Tracker*

Research publication data covering the years 2003 to 2023 was downloaded from the Web of Science (WoS) Core Collection database.[36] WoS Core Collection was selected because it's heavily used by researchers who study scientific trends, and it has well-understood performance characteristics.[37] This update also incorporates improved search terms to accurately capture technological trends in the 21-year period for each technology. Using those improved search terms, we downloaded 7.8 million publication records from WoS. We improved the quality of that dataset, most notably, by separating out, grouping (where relevant) and standardising country and institution names. We also filtered out retracted or duplicate records. Our final dataset contained 6.8 million unique publication records.

Improvements to our data-cleaning pipelines

In this update, we also developed a new method to semi-automate the cleaning of institution names by comparing the WoS and Research Organization Registry (ROR) databases to improve and expand our institution-cleaning dictionary.[38] We currently have a comprehensive database that includes more than 2,000 institutions from 86 countries, and we intend to expand that database further.

New historical data and future projections

For all our analysis, we used the top 10% most highly cited publications in each year to apportion equal credit to all authors; each author's contribution was equally apportioned to their respective affiliations and host countries.[39] Individual country and institution credits were summed up by publication year to track their high-impact research performance over the period of time being examined. Rankings were then generated for each technology based on their performance during the timeline being examined; for example, snapshots of performance in 2003–2007 and 2019–2023 data. In this report, we focus mostly on the top 5 countries and institutions in each technology.

The 21-year time-series graphs (below in the technology deep dives section of this report) show the countries' or institutions' individual yearly scores with a five-year average line to track their annual publication rate in the figures labelled (a) throughout this report. In order to take historical performance into account, the corresponding cumulative publications graph is plotted together with the five-year average trend line and is labelled (b) throughout this report. Partial average values are shown in the five-year average line at the edges (e.g. 2022, 2023) for ease of readability. A horizontal trend line indicates periods in which there were no additional high-quality research publications, suggesting that scientific output in that technology has more-or-less plateaued. In technologies such as *photovoltaics*, the research output graphs correlate well with reduced funding from government and the private sector.

For both graphs (a) and (b), we make projections from their recent historical trend (2010-2023) up to the year 2030 to predict whether or when the lead country will be overtaken in its publication rate and its cumulative publications, respectively. The intersection years for the US and China (for example, the year in which they reached parity) are summarised in Appendix 3 for all 64 technologies. While publication-rate parity can be an indication that two countries are publishing at the same rate, it isn't an indication that the countries are on par in terms of their scientific knowledge base. For example, in *advanced integrated circuits and design*, China overtook the US in its publication rate in 2021, but this is a technology for which, in 2003, the publication rate for the US was 35 times that of China and seven times that of the Netherlands (which had the second highest publication rate at that time). So, overall, the US remains in the lead if we consider their cumulative publications over the full 21-year timeline.

Why does historical research performance matter?

Measuring the past five years of high-impact research performance is a useful indicator of a country's research performance, strategic intent and potential future science and technology (S&T) capability. It provides a reliable snapshot of the pathway that a country or institution is now on, or at the very least aiming for—noting that of course, as we've raised earlier in this report, some countries and institutions are much better at commercialising their research findings than others.

Analysing long-term trends—in this case over 21 years—gives us deeper insights. It shows us which countries are gaining or losing ground, and when the trajectories countries are on and the extent of their momentum; where the public and private sectors are investing; and which universities, national labs, companies and government agencies are thriving, and in which technology areas. It also provides long-term insights into the spread, and concentrations of, global expertise in the 64 critical technologies.

This long-term dataset allows us to better unpack how China has built its stunning lead in high-impact research in the majority of critical-technology domains. While China's share of global highly cited research has steadily risen over the past two decades, the shares of technological pioneers—the US, the UK, Germany and Japan—diminished over the same period. In some technologies, such as *quantum sensors* and *advanced robotics*, multiple countries have been building their high-impact research output, but China's output has simply grown the fastest. In other technologies, such as *radar*, China's high-impact research output has been accelerating, while other leading countries have been in decline (for example, the US, Germany, Japan and the UK were ahead of China in 2003, but China overtook all of them by 2016.)[40]

A two-decade timeline is valuable because it tracks critical technologies within the lifetime of a valid patent.[41] This can give us insights into a country's existing scientific capabilities in areas that might not be reflected in its very recent research performance but can be seen when looking at long-term results. For example, we know that Taiwan currently produces 90% of the world's advanced semiconductor chips,[42] and yet in recent high-impact research output Taiwan ranks only 7th in *advanced integrated circuit design and fabrication* (semiconductor chip making), behind countries such as India and China (both of which are working hard to break into this technology). However, looking at the country's research performance between 2003 and 2007, Taiwan was in third place and between 2008-2010 was actually in second place (which is significant for a country with a small population).

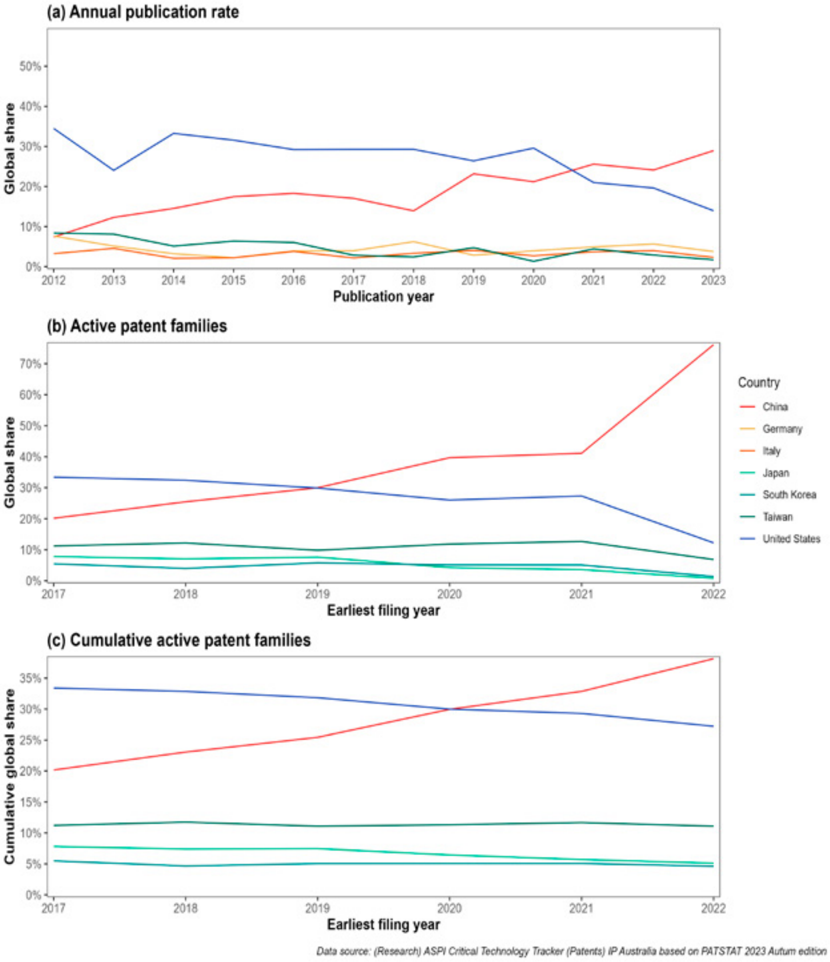
While a deep examination of patent data is outside the scope of this project, ASPI has also conducted some preliminary analysis to compare patent activity in select *Critical Tech Tracker* technologies. Like all indicators, patent data is imperfect, but it can provide complementary insights into innovation, commercial and industry trends.[43]

Our preliminary analysis (see Figure 2 below) covers the global share of active patent families from 2017 onwards. In short, a patent family is a set of patent applications related to a single invention and is deemed active when any application within that family is either valid or under review. The results shows that from 2017 onwards, Taiwan's output of both high-impact research and annual patent applications declines in terms of their global share, with Taiwan's high-impact research output flatlining in 2018 (reaching similar levels of output to Germany and Italy). Yet Taiwan is still able to maintain third position in the cumulative share of active patent families, behind China and the US.

These results help to show how Taiwan's historical and long-term research strength in semiconductor chip-making is a part of today's technological ecosystem, with Taiwan now viewed as a global semiconductor giant. That said, the cumulative value of the patents will of course eventually run out, again reinforcing the essential need for maintaining long-term investment in research and development.

The results also show China is gaining ground in the number of active patent family applications (and hence cumulative active family patent families) at the expense of the US's global share. With China taking over the US in both high-impact research output and patent activity, and with output continuing to trend upwards in both metrics, China has put itself in a far better position today, than just five years ago, to capitalise on its scientific gains and breakthroughs in *advanced integrated circuit design and fabrication*.

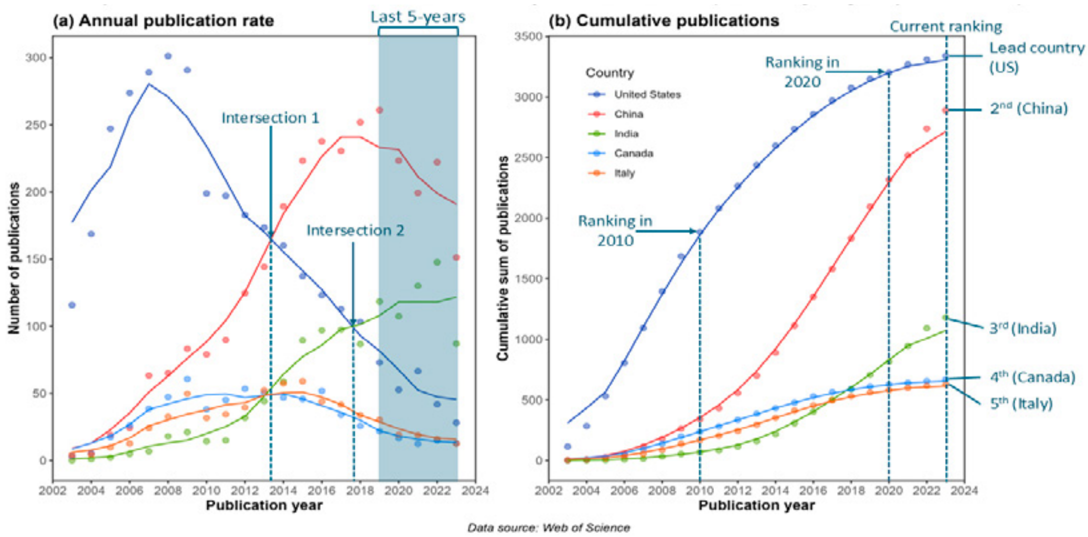
Figure 2: Comparing the top 5 countries in the (a) global share of high-impact research publications, (b) the global share of active patent families filed in each year and (c) the cumulative global share of active patent families active as of 2023 filed per year in *advanced integrated circuit design and fabrication* (countries ranked by historical performance). A patent family is the set of patents related to a single invention. The earliest filing year is the earliest year that a patent related to each patent family was applied for.



Two decades is also the approximate time it would take for a developing country to build up scientific capability, attract talent and establish institutional support for world-leading research.[44] The scarcity of developing countries in the top 10 rankings (for example, the minimal presence of Southeast Asian countries) shows just how hard it is, and how long it can take, to build a competitive advantage in these fields—which are often already highly competitive. In addition, ASPI's *Talent Tracker,* which reveals the flow of global talent in these technologies, helping to highlight brain gains and brain drains for each country,[45] demonstrates the difficulty for Asia, and India especially, in retaining early-career researchers who go on to conduct high-impact research, primarily in the US and Europe. At the macro level, the new 21-year dataset shows us that time, money, talent and, ideally, a strategy are needed to develop a strong foundation of high-performing scientific expertise.

Tracking the long-term trajectory of *mesh and infrastructure-independent networks* provides another valuable example of the value of examining historical research performance.[46] Figure 3(a) shows high-impact publication rates over the past five years (highlighted in blue). In that window, China is ranked first, followed by India, the US, the UK and Canada. But this recent snapshot in time lacks the context that a historical perspective can provide. Our 21-year dataset shows that the US had a prominent lead in this field, with a peak in its publication rate in 2008. That potentially gave the US an early opportunity to patent its findings and capitalise on breakthroughs ahead of the other countries. We also need to keep in mind that, as we have raised elsewhere in this report, all countries engage in classified and commercial-in-confidence research (and some scientists wear dual hats and produce both public and classified work concurrently). Because the US has peaked earlier than China in certain technologies, it's possible that, in a range of sensitive technology areas, the movement of work to classified systems in the US happened earlier than in other countries.

Figure 3: How to read the graphs in this report: (a) number of publications per year and (b) cumulative publications for the years 2003 to 2023



Note: This example is for mesh and infrastructure-independent networks.

Figure 3(b) shows country performance using 2003 as the starting point, highlighting differences in the country rankings between 2010 and 2020, and showing India overtaking Canada and Italy within that decade. We can read their 2023 rankings, based on their 21-year performance, in Figure 3(b), which shows the US leading ahead of China because of the substantial historical advantage that the US had in this technology. This estimates the gap in foundational scientific knowledge that China and the other competing countries must bridge to be on par with the US's long-term performance. The intersection years are points in time when the US and China are on par in their publication rates. The intersection years were extracted from the 21-year datasets for the 64 technologies and are summarised in Appendix 3.

China's research lead and capability: sometimes it's ahead; other times it's trying to catch up

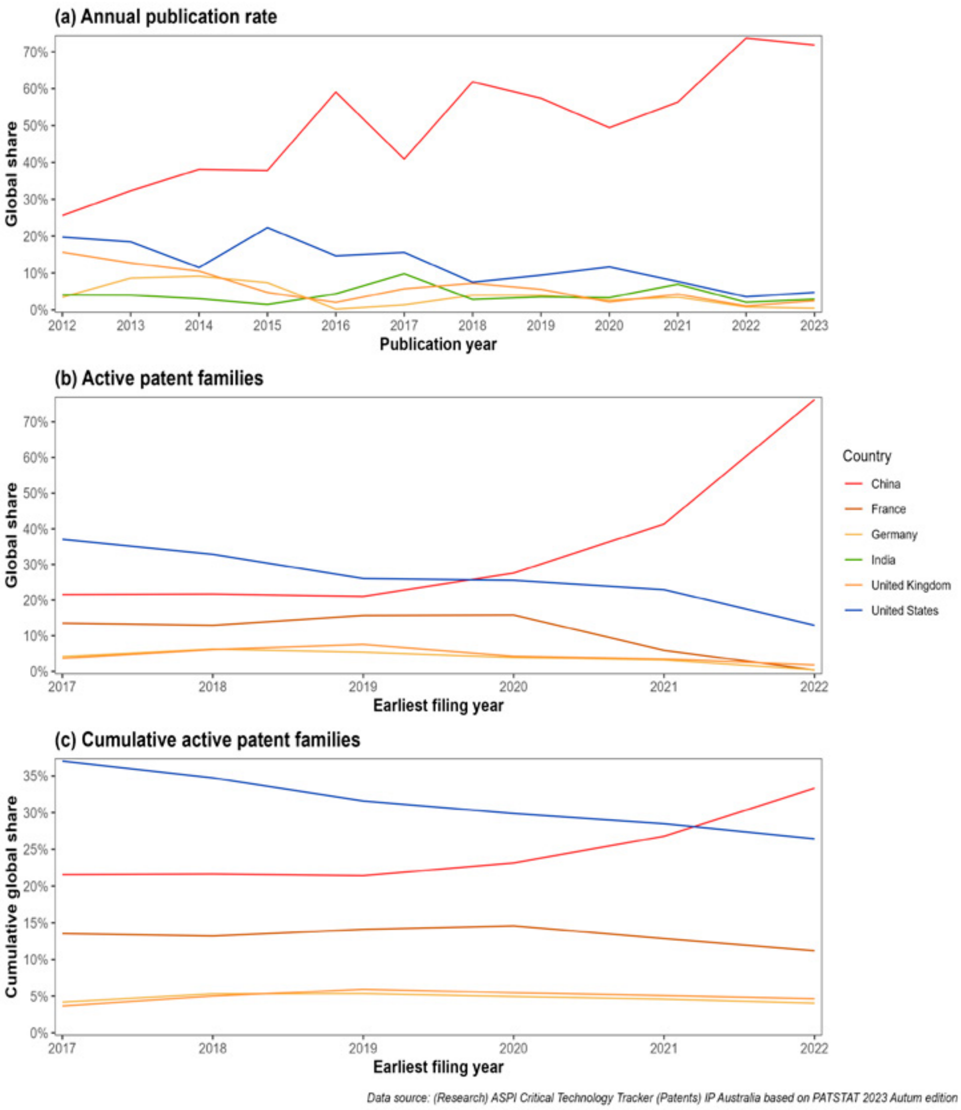
As ASPI argued in our 2023 report, which launched the *Critical Technology Tracker*,[47] China is building the foundations to become the world's leading S&T superpower by establishing an often-dominant lead in high-impact research in most critical and emerging technologies. However, as we've highlighted above, and previously, China's dominant high-impact research performance across so many technologies doesn't necessarily equate to the same dominance in actualising those technologies.

At times, China is ahead in high-impact research because it's actually behind in the development and commercialisation of that technology and is making major investments in S&T to try to catch up to the advances made by other countries over previous decades.

In *advanced aircraft engines*, for example, 10 out of 10 of the world's top-performing institutions in the *Tech Tracker* are in China, and the country currently produces over 70% of the world's high-impact research (see page 29). Currently the top two ranked institutions are, in first place, the People's Liberation Army's (PLA) premier institution for scientific research and education, the National University of Defense Technology,[48] which sits under China's Central Military Commission and, in second place, the Nanjing University of Aeronautics and Astronautics[49] which is one of China's 'Seven Sons of National Defence'.[50] In the 2003-2007 rankings, those top two positions were held by NASA and the US Air Force Research Laboratory. China's now extremely dominant research performance results – and the types of institutions leading that effort - show the country's strategic effort to catch up to others that have a historical lead in both aircraft-engine manufacturing and air force capability—in particular the US.[51]

When looking further down the S&T life cycle, at patent data for example (Figure 4), there is a closer and more recent competition. The overall trends, however, are similar. China's high-impact research output rates, which overtook the US during 2011, have been trending upwards ever since. However, up until 2019 the US still had the highest number of active patent family applications filed per year, and up until 2021 it was ranked 1st in cumulative active patent families. But, since 2017, China has increased their global share in both patent metrics, at the expense of the US, and as of 2022 is leading in both.

Figure 4: Patent family filings and annual publication rate in *advanced aircraft engines* (countries ranked by historical performance)



If we look at other defence technologies, for example, China is leading in research performance in *high-specification machining processes*, *advanced composite materials* and *hypersonic detection and tracking*. Those are important technologies that underpin a modern military, and they're technologies in which the US has traditionally led in R&D and manufacturing and is currently more technologically advanced than China. In some of those technologies, China's lead in research performance reflects its efforts to catch up. However, in other technologies, such as *drones, swarming and collaborative robots*, China isn't playing catch-up, as it excels at both research performance and technology capability: 90% of commercial drones used in the US are manufactured in China.[52]

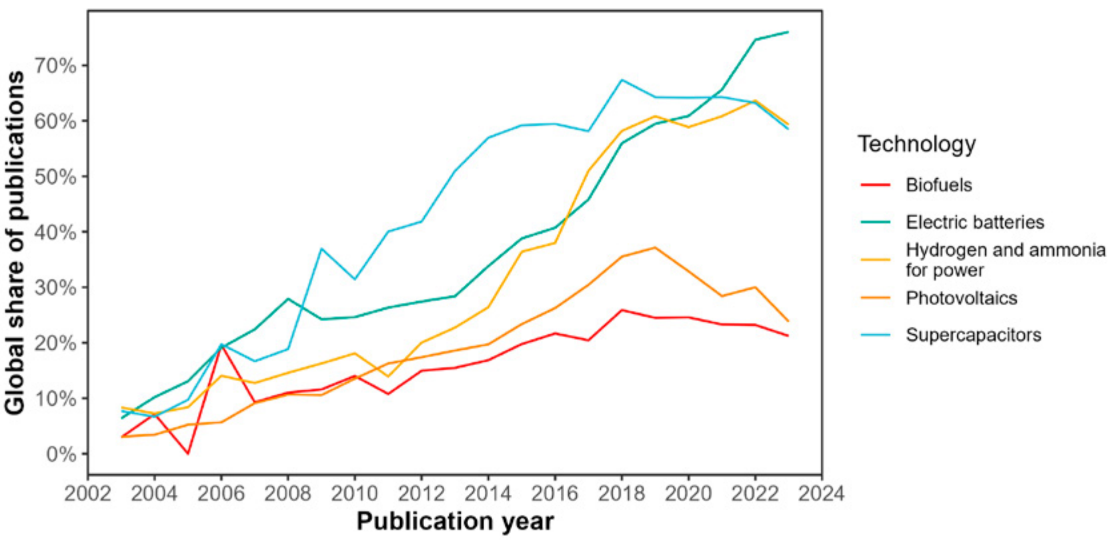
There are also some technologies in which the US and European countries aren't publishing as much high-impact research as they were two decades ago or have flatlined while China has increased its research output dramatically. In some cases, this will be, at least partially, because previous leaders have moved a share of their work to patents and, in some fields, to classified systems and commercial-in-confidence labs (obvious examples include defence relevant technologies such as *air-independent propulsion*, *autonomous systems operation technology*, *autonomous underwater vehicles* and *directed energy technologies*).

However, there are also likely many cases in which previous research dominance has given way to a business-as-usual approach as many countries and institutions underestimated the extent of the changing strategic environment and the intensity of competition that started emerging decades ago, leading to flat or declining output despite the evident advances being made by China.

Electric batteries provide one of the strongest examples in which China has translated consistent high research performance (see page 32) over the past 21 years into technological gains, and then market dominance. It's also a prime example of a technology in which the US and Japan have fallen behind, despite both being pioneers in the technology in the 1980s. It was the work done in both the US and Japan that led to the development of the lithium-ion battery, which currently dominates the electrochemical energy storage market.[53] But, over 20 years ago, the Chinese government made a strategic decision for China to become a world leader in electric vehicle (EV) manufacturing, which they have been successful in.[54] In addition to research excellence, other factors mattered, including China's reported spending of US$29 billion between 2009 and 2022 on relevant subsidies and tax incentives to support any company involved in making EVs.[55] China also strategically appointed technically skilled individuals to senior roles; for example, it appointed Wan Gang, an experienced auto engineer with work experience at Audi in Germany, as Minister of Science and Technology in 2007. Today, the production of electric batteries is heavily skewed towards China (77% in 2022);[56] the top two EV battery manufacturers, Contemporary Amperex Technology Co. Limited (CATL) and BYD, are responsible for half of global production of EV batteries (including those used in the Tesla Model Y).[57]

The 21-year results clearly show that China's high-impact research output in *electric batteries*, and in other energy and environment relevant technologies including *photovoltaics*, *hydrogen and ammonia for power* and *supercapacitors* ramped up in the early 2000s (Figure 5). There was a clear strategy, and China prioritised those technologies to diversify energy options and build new renewable energy industries.[58]

Figure 5: Trend in China's global share of annual high-impact publication rate in technologies in the energy and environment category



Data source: Critical Technology Tracker

The Chinese Academy of Sciences: innovation, commercialisation and whole-of-nation strategy

The Chinese Academy of Sciences (CAS, 中国科学院), the world's best-performing institution in the *Critical Technology Tracker* with a lead in 31 of 64 technologies (an increase from 29 last year), is more than a research institute. CAS plays a vital role in China's whole-of-nation approach to S&T policy and has been at the centre of the country's major technological breakthroughs since the founding of the People's Republic in 1949.

CAS, a ministerial-level institution sitting directly under the State Council, has spearheaded the development of China's indigenous science, technological and innovation capabilities, including in computing technologies, nuclear weapons and intercontinental ballistic missiles.[59] It's believed to be the world's largest scientific institution,[60] with a reported departmental budget of US$23.8 billion in 2023,[61] more than 69,000 employees, investment arms[62] and a large number of branches, institutes and national labs.[63] CAS has a robust internal communist party apparatus, and CAS members are required to 'model love of the Party', 'serve national security' and follow the policies of the Chinese Communist Party's Central Committee.[64] At least seven of its institutes are subject to US Government restrictions.[65]

CAS specialises in commercialising its findings and creating new companies. That approach can be traced back to 1985, when CAS undertook a reform named 'one academy, two systems' (一院两制), which encouraged its research institutes with application capabilities to enter the market.

According to CAS, by 2022 more than 2,000 companies had been founded from the commercialisation of its scientific research.[66] Companies that CAS has established or helped to create include Lenovo (personal computers and electronics),[67] iFlyTek (AI),[68] Sugon (supercomputers),[69] Cambricon Technologies (AI chips)[70] and Loongson (advanced chips).[71] A number of them have been added to the US Entity List over the past five years for reasons ranging from links to China's military modernisation to human-rights violations.[72] CAS is also an investor, and Chinese business database site *Qichacha* lists it as a shareholder in 222 companies directly and another 971 indirectly.[73]

National security is part of CAS's mandate,[74] and there are collaborations between its institutes, the PLA and other public-security institutions. In 2018, for example, CAS signed a strategic cooperation framework agreement with the PLA's Academy of Military Sciences (中国人民解放军军事科学院).[75] There's also overlap in staff, as many leading experts from the Academy of Military Sciences are academicians at CAS.[76] In 2020, CAS and the Ministry of Public Security (公安部) jointly established the Laboratory of Cyberspace Geography (网络空间地理学实验室).[77]

CAS is reportedly leading around 30 major and national infrastructure projects, including China's Remote Sensing Satellite Ground Station[78] and the High Precision Ground-based Time Service System, which will reportedly integrate space- and ground-based signals.[79]

CAS is also a member of a new, ambitious electrical battery consortium established in January 2024: the China All-Solid-State Battery Industry–University–Research Collaborative Innovation Platform (CASIP, 中国全固态电池产学研协同创新平台).[80] Other members include government ministries, companies (such as CATL and BYD), investment funds and research institutes (in addition to CAS, which is leading in the *Tech Tracker* for *electrical batteries*, Tsinghua University, which ranks 2nd, is also a member).[81] Senior CAS staff were involved in the establishment of CASIP, which aims to 'better realize the integration of production, education, research and application and strive to promote the industrialization of solid-state batteries'.[82]

The CAS leadership has reportedly developed a diversification plan to avoid 'choke-points' after many of its strategically important companies were placed under US sanctions. In 2020, then CAS President Bai Chunli (白春礼) said that, 'faced with the US suppression of China's high-tech industries, the US "choke point" list will be turned into a list of scientific research tasks for the Chinese Academy of Sciences'.[83]

Technology deep dives

In this section of the report, we focus on 10 of the 64 technologies in the *Critical Technology Tracker*. For each technology, we track the evolution of top-ranking countries and institutions over the recent five-year period (2019–23) and we compare those with the earlier five-year periods, such as 2003-2007 and 2011-2015, to show what has changed and evolved over time. We also analyse the accumulation of high-impact publications to show which countries have built up a strong foundation of high-performing institutions and scientific expertise. This long-term dataset shows the trajectory that different countries, and institutions, have taken and allows us to better pinpoint when major changes, increases or decreases, have occurred.

In select technologies, we have also taken a more recent slice of the historical data (2010-2023) to make future projections, based on current trends, up until 2030 for China and the US, which helps to illustrate where momentum currently lies.

Next to the heading of each technology below is a coloured circle—red (high), orange (medium) or green (low)—which highlights each technology's monopoly risk rating based on the share of high-impact research output and the number of leading institutions the dominant country has (these circles are also now present when you select technologies via techtracker.aspi.org.au. For more on the technology monopoly risk rating, see Appendix 1). Of the ten technologies below, China is leading in seven and the US in the remaining three.

Not all graphs are shown in these deep dives, but the results are summarised in Appendix 3.

1. Advanced integrated circuit design and fabrication

Out of all 64 technologies in the *Critical Technology Tracker, advanced integrated circuit design and fabrication* (in simple terms, advanced semiconductor chips) has seen some of the fiercest global competition, particularly between the US and China (see box below). The semiconductor chip industry has focused on exponentially shrinking semiconductor chips to make them faster and cheaper. In 2003, design and fabrication processes were optimised for chips in which the smallest feature on the chip was 90 nanometres (nm). Now, in 2024, design and fabrication processes are optimised towards scaling the smallest feature on the chip down to 2-nm. Because the scaling happens in all three dimensions, completely different processes (and tools) are required for every generation of chips.

Global semiconductor competition

To secure the US semiconductor industry, with bipartisan support, the Biden administration signed the CHIPS and Science Act into law in August 2022. The Act, which focused on boosting local semiconductor chip fabrication, was supplemented in October 2022 by formal restrictions on the export of US-made advanced chips and semiconductor fabrication tools to China, as well as restrictions on US residents supporting the Chinese chip-manufacturing industry.[84]

The global semiconductor sector—including its revenue, investments and future developments—has been affected by those export restrictions. The Dutch company ASML is currently the only manufacturer of extreme ultraviolet (EUV) lithography instruments, which are the key to the most advanced chips (2–3 nm). Even though ASML hasn't been allowed to sell EUV systems to China since 2019, further export restrictions were imposed on the company's deep ultraviolet (DUV) systems in October 2023.[85] ASML's strength in this area previously benefited from research and knowledge sharing from US national labs.[86]

One of ASML's close partners is IMEC (in Belgium), a global R&D leader in chip manufacturing, which is currently ranked 5th in the *Tech Tracker* in *advanced integrated circuit design and fabrication*. IMEC has historically taken a neutral stance in the technology competition between China and the US in the chip industry. In 2002, IMEC signed a long-term partnership with China's partially state-owned Semiconductor Manufacturing International Corporation (SMIC), thus kickstarting SMIC's ambition as a global leader in chip manufacturing. SMIC established the SMIC Advanced Technology Research and Development Corporation in 2015 in a joint venture with Huawei, Qualcomm and IMEC focused on next-generation CMOS (complementary metal–oxide–semiconductor) logic technology.[87] Recently, IMEC has announced a drastic reduction in its partnerships with China, including a rollback of its ongoing obligations on mature chip technologies, reflecting the current geopolitical tensions affecting China in the chip industry.[88]

Those sanctions have been effective to some extent in reducing China's current ability to make advanced chips, and are hindering its progress in other related technologies such as *quantum computing* and several within AI.[89] In response, China has boosted investment into advanced chip technology R&D and poured billions of dollars in funding from the central and provincial governments into Chinese semiconductor companies.[90] In addition, Chinese AI-focused research institutes and universities have sourced Nvidia chips despite the US export restrictions through sales to largely unknown Chinese companies.[91] The beyond-expectations performance of Huawei's 2023 flagship phone, the Huawei Mate 60 Pro, puts into perspective China's semiconductor chip fabrication capabilities, in particular those of SMIC.[92] Reverse-engineering of the Huawei Mate 60 Pro has revealed that SMIC has managed to achieve 7-nm nodes in its Kirin 9000s chipset by running the lithography step four times—a process previously used by TSMC to reduce the device size without EUV lithography. The detailed video of that analysis further revealed China's capabilities in *wide and ultrawide bandgap semiconductors* for power management.[93]

The US proposal for the 'Chip 4 Alliance', bringing together the four largest semiconductor manufacturers of the US, Taiwan, South Korea and Japan, has the potential to further limit China's advanced semiconductor chip manufacturing ambitions if collaboration between the four countries continues to gain momentum.[94] China retaliated by imposing export restrictions on key materials in semiconductor manufacturing: the rare-earth metals gallium and germanium and related compounds.[95]

China's ambition in semiconductor manufacturing goes beyond the 7-nm generation, which is at present limited by its EUV lithography capabilities. China's Tsinghua University, which is currently ranked 9th in this technology in the *Tech Tracker*, is reportedly building a particle accelerator (100–150 metres in diameter) for EUV light sources.[96] To achieve commercial viability, it's expected this process will be both costly and complex.[97]

Country performance and projections

Comparing the rankings across the 21-years, the most notable changes have been the disappearance of the Netherlands and Taiwan in recent rankings and the emergence of China. The drop has been more significant for the Netherlands, which went from ranking 2nd in 2003–2007 to 20th in 2019–2023. Although not currently in the top 5, Taiwan has a history of strong research performance, and it currently ranks 7th.

Figure 6(a) below shows the US maintaining a comfortable lead in high-impact research until the 2010s, at which point China and Taiwan both began increasing their research outputs. For Taiwan, this was a rather modest increase, and they were not able to sustain it for very long. In contrast, China has continued to increase its high-impact research output and overtook the US in its annual publication rate in 2020. The US's early lead, however, gives it a comfortable advantage in cumulative publications (Figure 6(b)).

Projections for the cumulative publications by the US and China (Figure 7) show that, despite China's acceleration in research output, it will be difficult for China to bridge the gap. If current trends continue, the US will still have a higher cumulative total in the years beyond 2030.

Figure 6: Top 5 countries in *advanced integrated circuit design and fabrication* (ranked by 21-year performance)

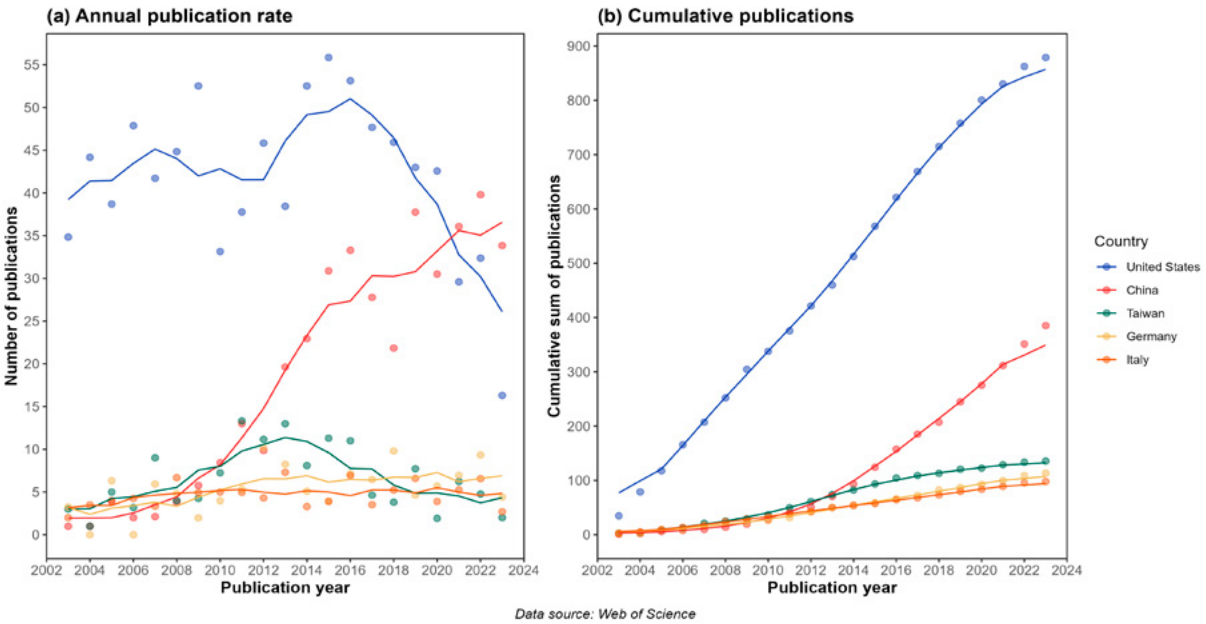
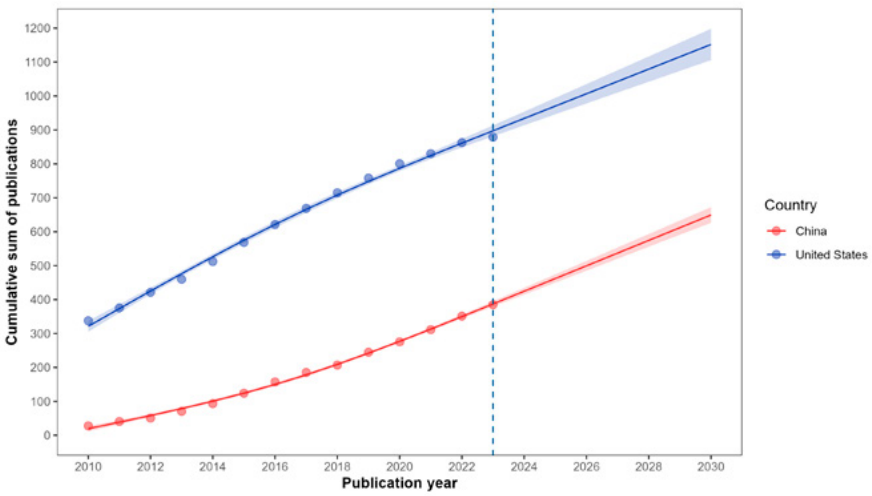


Figure 7: Projection of cumulative publications in *advanced integrated circuit design and fabrication* for the US and China to 2030 (blue broken line indicates the start of the projection); the 95% confidence interval bands are shown in shaded regions around the projection lines



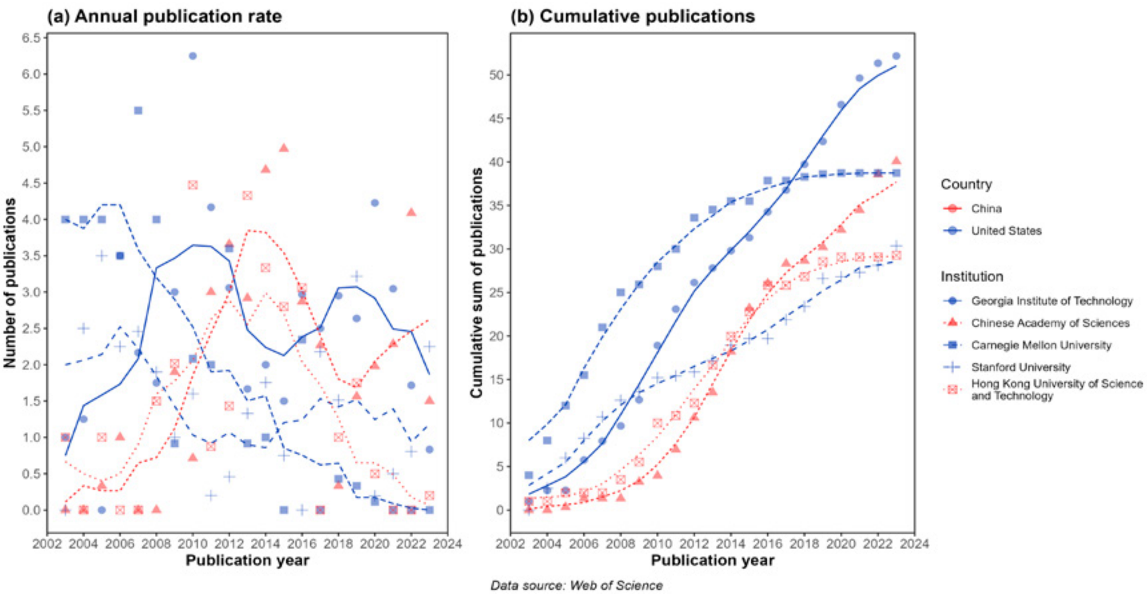
Institution performance

When ranked by research performance between 2003 and 2007, the top 7 institutions in *advanced integrated circuit design and fabrication* are all based in the US, with the exception of Philips in the Netherlands, which ranked 3rd. Philips used to be globally recognised for its research laboratories, in a similar way to the US's AT&T Bell Laboratories. An early investor in ASML[98] and TSMC[99], Philips split its branches into different spin-off companies and underwent a series of re-structures in the early 2000s which reduced its research capacity especially in semiconductors.[100] Some of these commercial changes and divestments help to explain the gradual disappearance of Philips from the top 5 institutions in *advanced integrated circuit design and fabrication*.

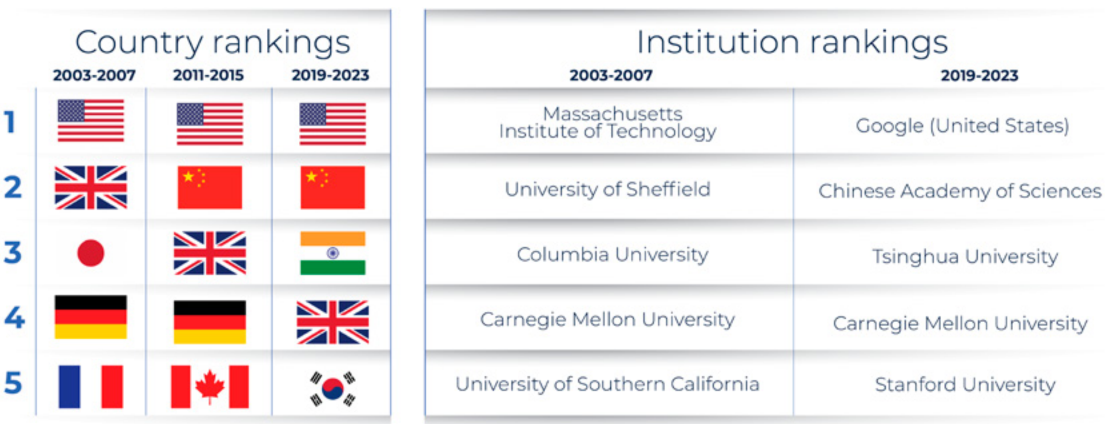
Despite leading the world in high-impact publications in 2003, Carnegie Mellon University's contribution to the field trended towards minimal output over the 21-year period (Figure 8), with two notable exceptions in the following years, after the university received funding from DARPA[101] (2007) and Intel[102] (2012). Carnegie Mellon's reduced performance from 2018 onwards allowed CAS to squeeze past into 2nd place in 2023.

The Georgia Institute of Technology (Georgia Tech) is currently the leading institution in *advanced integrated circuit design and fabrication* research, which most likely contributed to its inclusion as one of the US institutions receiving funding under the CHIPS Act.[103] Peking University and the University of Florida, although latecomers to the field, have in recent years outperformed more established institutions such as Stanford University and Penn State University. IMEC in Belgium, one of the world's largest semiconductor R&D organisations, entered the top 5 rankings for its recent performance, although it has maintained a consistent high-impact publication rate throughout the 21-year period.

Figure 8: Top 5 institutions in *advanced integrated circuit design and fabrication* (ranked by 21-year performance)



2. Natural language processing



Natural language processing (NLP) is a field of AI that uses computational linguistics and statistical modelling to enable computers to process and generate naturally developed languages at a level that's indistinguishable from a human interaction. Breakthroughs in deep learning over the past two decades have made such interactions possible, using large language models (LLMs) trained on growing volumes of data.

Country performance and projections

Two interesting points in the NLP top 5 country leader board for the three 5-year periods is the notable absence of China in the 2003–2007 ranking and the gradual drop of the UK's ranking across the three periods.

2010 was a pivotal point in NLP, bringing, for example, major advances in recurrent neural networks[104] and word vectorisation. The timing of such advances coincided with rapid increases in the US's and China's high-impact publication rates (Figure 9). The US occupied a dominant position in high-impact NLP research throughout most of the 2000s and 2010s, but the gap in publication rates between them has narrowed rapidly over the past five years, and China reached parity with the US by 2021. The steady growth of India's high-impact publication rates after 2010 allowed them to surpass Germany and the UK despite the two countries' continuous, yet more subdued, growth. With a five-year delay (starting in 2016 instead), that growth was mirrored by South Korea as well.

The US's strong historical performance has meant that it has maintained a significant lead in cumulative publications in the field. Our projections for the US and China to 2030 (Figure 10) show that the US will still lead, cumulatively, if it maintains its current publication rate.

Figure 9: Top 5 countries in *natural language processing* (ranked by 21-year performance)

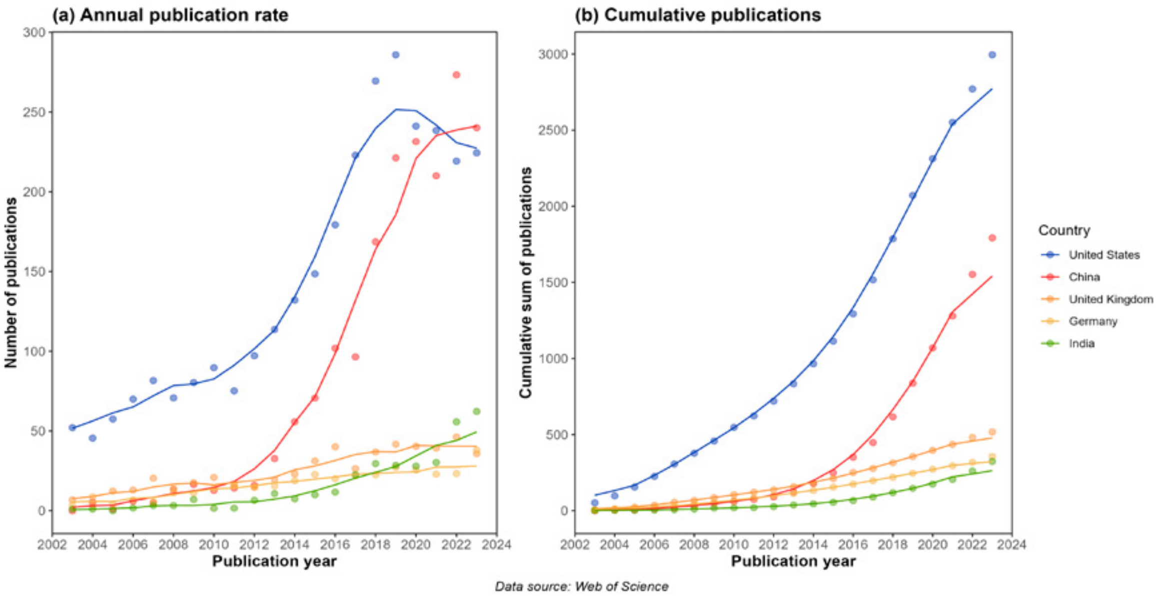
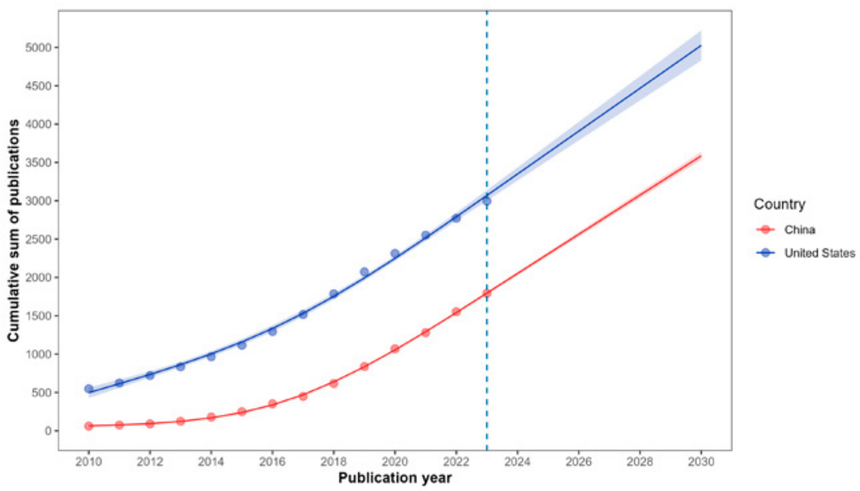


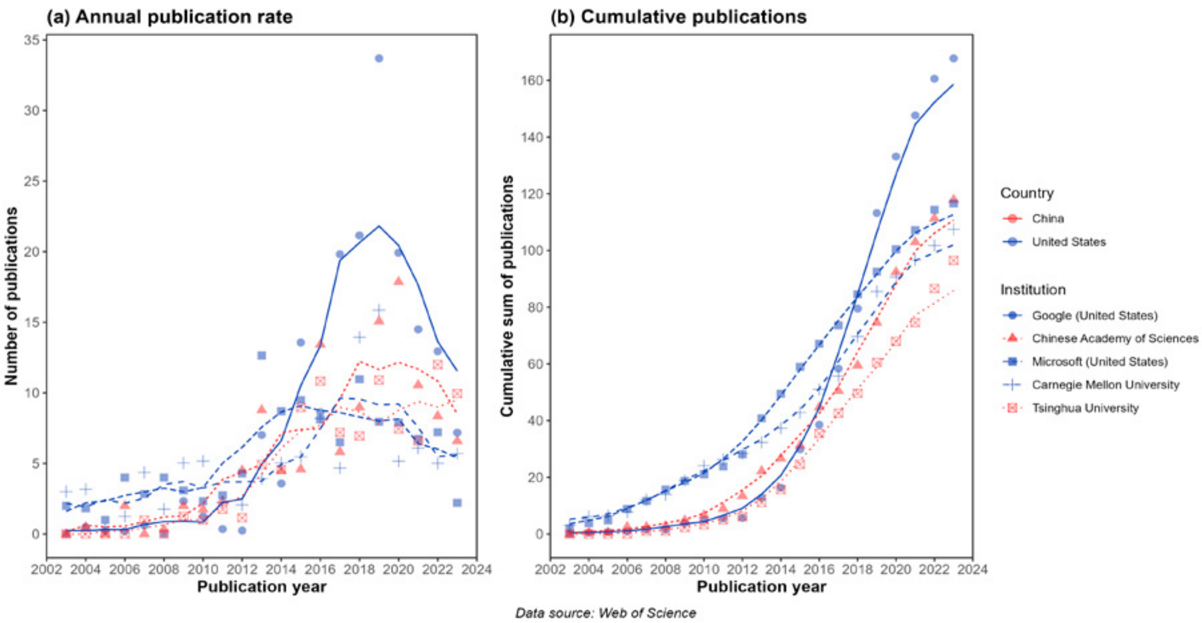
Figure 10: Projection of cumulative publications in *natural language processing* for the US and China to 2030



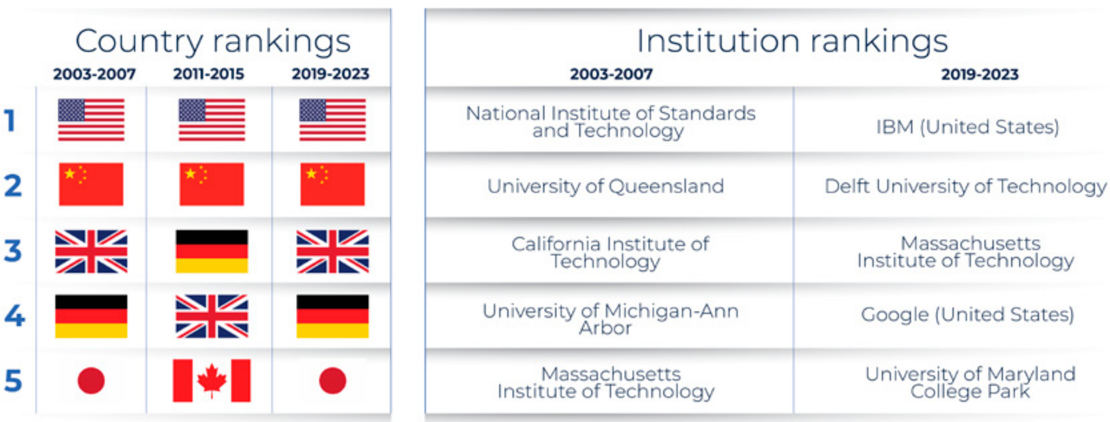
Institution performance

Before 2010, NLP research was dominated by a handful of US-based institutions, led by Carnegie Mellon University, the Massachusetts Institute of Technology (MIT) and Microsoft (see table above and Figure 11). The University of Sheffield is the only non-US institution in the top 5 institutions in the 2003–2007 ranking. Perhaps partially spurred by the commercial consequences of the successful launch of Apple's Siri virtual assistant in 2011, the first of its kind, Google rapidly increased its publication rate from 2012 onwards, establishing new divisions such as Google Brain in 2011 and acquiring the UK start-up DeepMind in 2014. These strategic decisions helped to boost Google's ranking, which was leading in high-impact publication output between 2017-2022. Microsoft, a historically strong performer, is 3rd across the full 21-year period because of its leadership in the intermediate five-years (ranked 1st in the 2011-2015 snapshot) but it has slightly subsided in recent years (from 2016). While the best LLMs, such as Sora and GPT-4, are testimony to the US's strength in this technology, the emergence of CAS and Tsinghua University in the top 5 institutions (2019-2023 ranking) is part of China's efforts to catch up, and it's clearly making gains.

Figure 11: Top 5 institutions in *natural language processing* (ranked by 21-year performance)



3. Quantum computing



Quantum computing describes computers that can use quantum states to perform certain computations in a fraction of the time required to perform the same tasks on classical computers. Developing a *quantum computing* capability is a national technology priority for many countries, and governments and private investors are investing huge sums into its development.[105]

Country performance and projections

The top 5 countries leader board shows minor difference across the three 5-year periods, with Germany and the UK vying for the 3rd and 4th places across the last two decades. The most interesting feature in Figure 12(a) is a turning point in the high-impact publication rate for the US in 2016 and for China in 2020. Those large increases roughly correspond to the start of competition between tech companies such as Google and IBM to build the world's most powerful quantum computers.[106] That uptick was mostly confined to the US and China, but the other top-ranking countries showed a relatively steady publication rate throughout the 21-year period.

Despite China's progress in this technology, it hasn't surpassed the US. In fact, this is one of the few technologies in which the two countries have diverged over the whole period. China is struggling to catch up, let alone keep pace, with the US. Our projections show that, if current trends continue, the US will remain ahead of China until at least 2030.

Figure 12: Top 5 countries in *quantum computing* (ranked by 21-year performance)

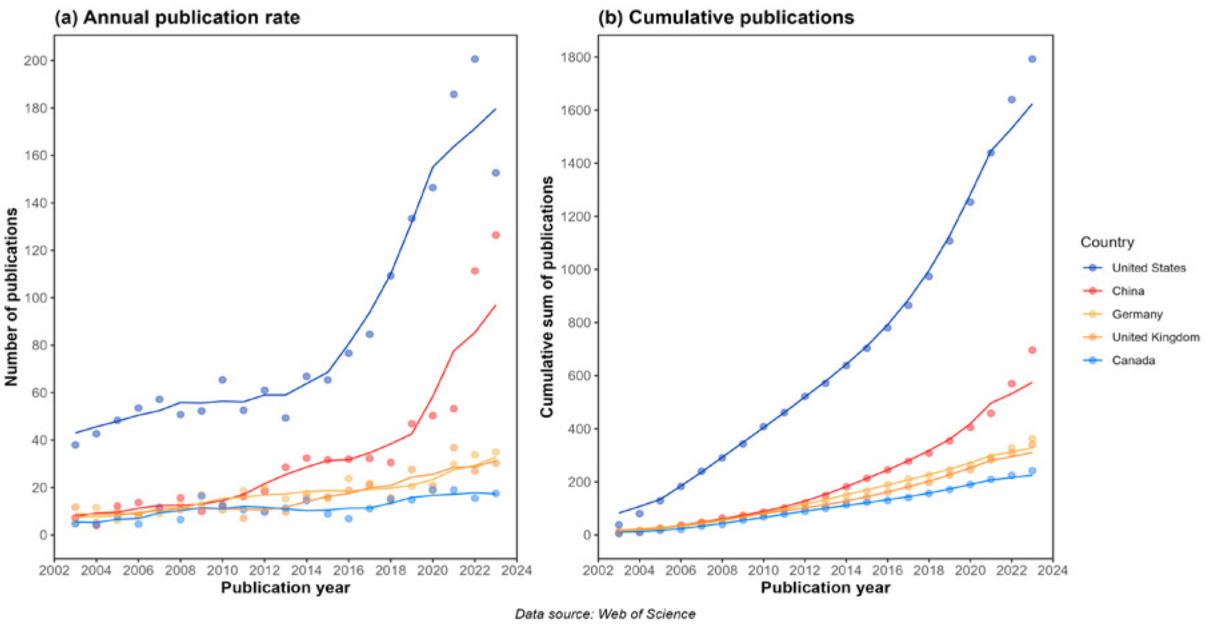
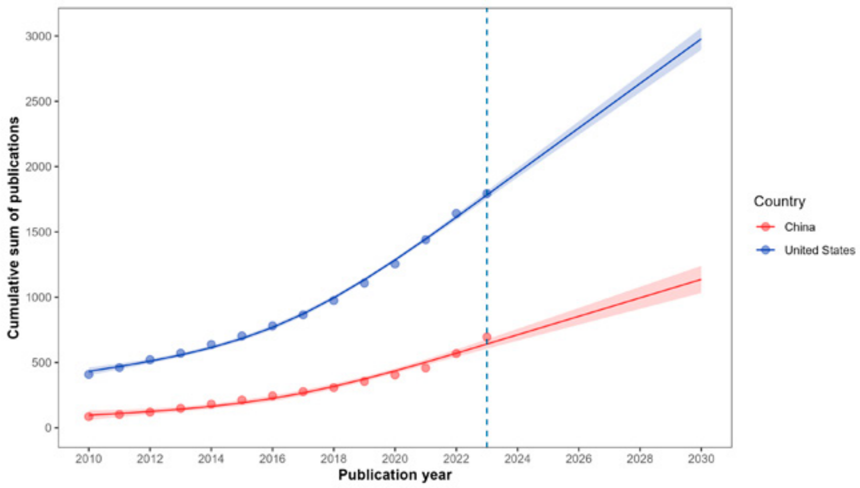


Figure 13: Projection of cumulative publications in quantum computing for the US and China to 2030

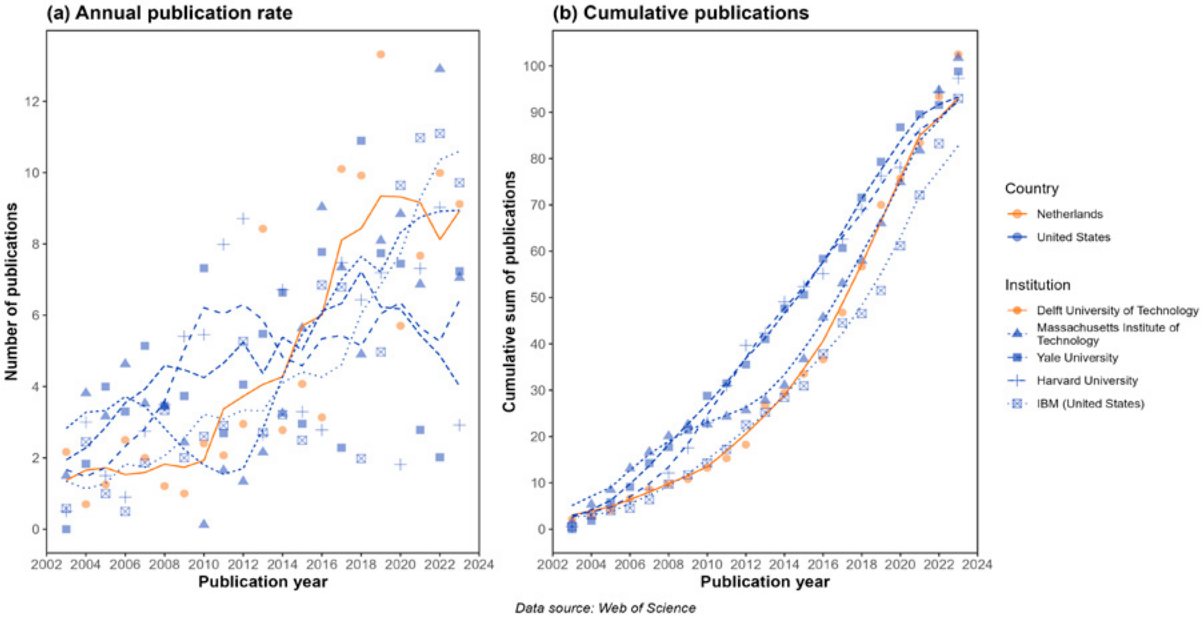


Institution performance

The top 5 institutions in quantum computing show the strength of the US in *quantum computing*. The top-ranking institutions in 2003–2007 were mostly based in the US, with the exception of the University of Queensland. When compared to the recent top 5 (2019-2023), the top 5 institutions is still US dominated with the exception of Delft Institute of

Technology (2nd) and the only common institution is MIT which improved in its ranking across the two periods. The main change in the top 5 in recent years is the rise of two US technology companies – IBM (1st) and Google (4th). Google was absent from this field of research prior to 2014.

Figure 14: Top 5 institutions in *quantum computing* (ranked by 21-year performance)



4. High-specification machining processes

Institution rankings

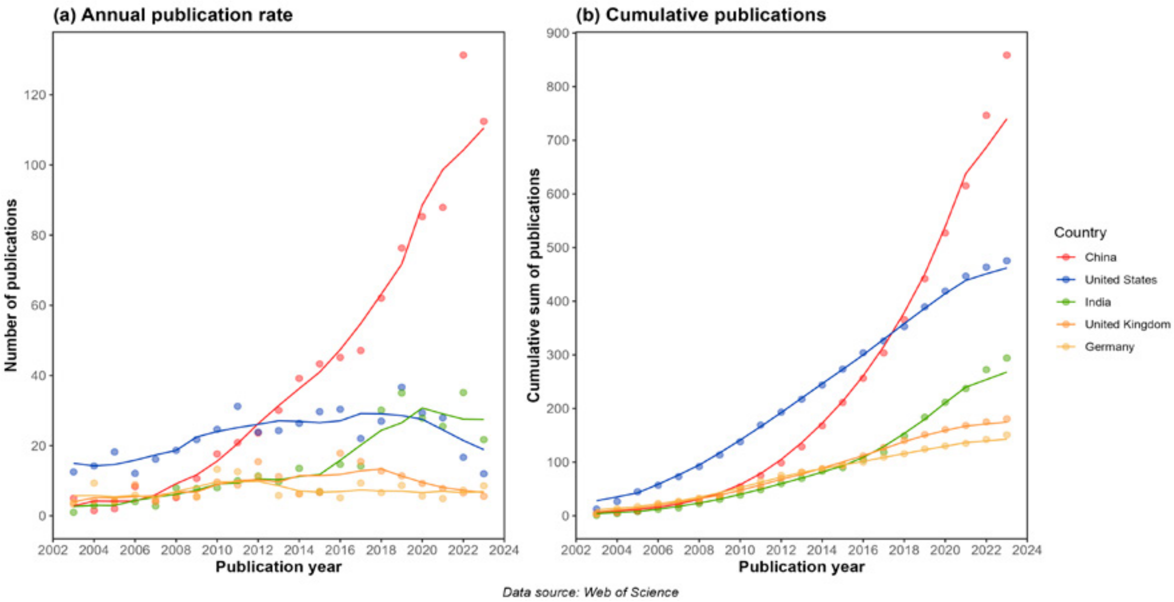
2003-2007	2019-2023
National University of Singapore	Harbin Institute of Technology
Nanyang Technological University	Dalian University of Technology
National Central University	Chongqing University
National Cheng Kung University	Hong Kong Polytechnic University
Jadavpur University	Chinese Academy of Sciences

High-specification machining processes cover the precision manufacturing of parts to submicron (less than a millionth of a metre) levels through milling, cutting and machining. Such processes have applications in the manufacturing of medical devices (high-precision surgical scissors, vein cannula casing and precision bone saws in orthopaedic surgery) and aircraft parts (from aircraft turbines to advanced engines).

Country performance and projections

There's a marked contrast in how the publication rates of the top-performing countries evolved over the 21-year period. The US, the UK and Germany all showed gradual increases before trending downwards (Figure 15(a)). For Germany, that was in 2012, followed by the UK in 2018 and the US in 2020. In contrast, China's publication rate grew consistently throughout the period, and it has already exceeded the US in its cumulative publications (Figure 15(b)). To a lesser extent, that growth is also observed for India, making this one of the few research areas in which India's high-impact publication rate currently exceeds that of the US (although India's output has levelled in recent years). It's worth noting that the strength of the top-performing countries in this technology has meant that only India has managed to crack into the top 5 over the 21-year period. Turkey has also made considerably gains over the decades as well, however, and when combined with the UK's recent slump may see it soon reach fifth place as the UK falls from the rankings.

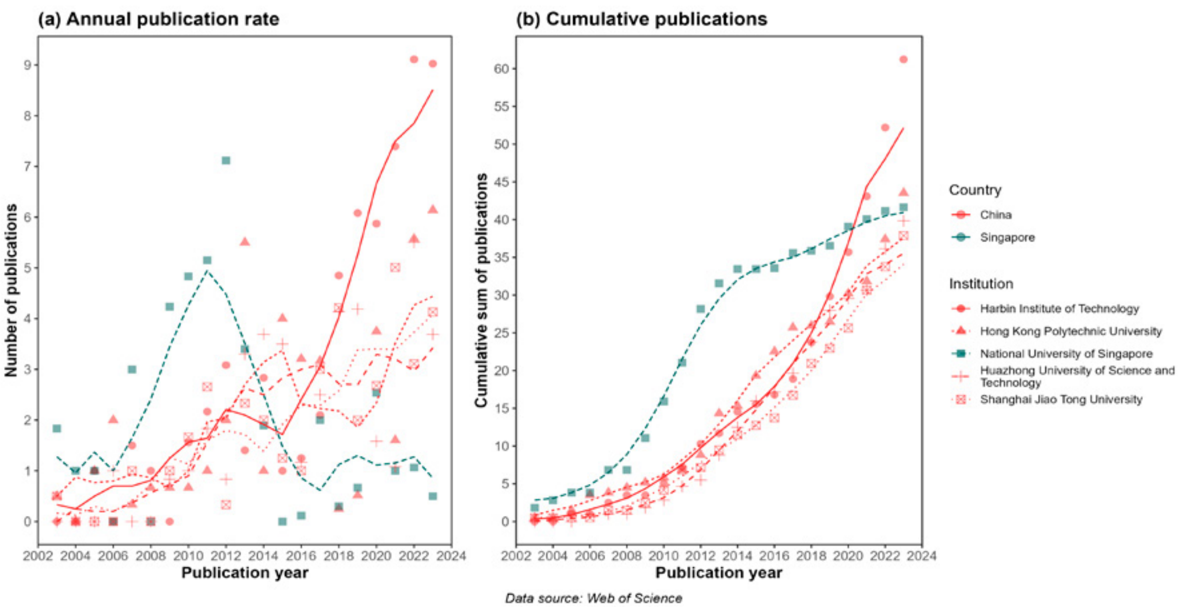
Figure 15: Top 5 countries in *high-specification machining processes* (ranked by 21-year performance)



Institution performance

The top 10 institutions in 2003–2007 were predominantly based in Singapore and Taiwan. In contrast, the top 20 institutions in 2019–2023 are all based in China, with the exceptions of the Indian Institute of Technology Bombay (10) and the Indian Institute of Technology Roorkee (14). The National University of Singapore, which was the world-leading institution in 2003–2007 saw its high-impact publication rate peak in 2011 before subsiding to average levels (Figure 16(a)) and now ranks 28th. The recent strong performers of Dalian University of Technology, Hong Kong Polytechnic University and CAS all show steady improvement over the 21 years. The Harbin Institute of Technology represents the most notable institution change, however. Having ranked 16th in 2003–2007, it now occupies a leading position. The institute, which has been on the US sanction list since 2020,[107] is one of China's most important defence universities[108] and also ranks highly in *advanced aircraft engines* research. It has long been a hub of Sino-Russian research and technological cooperation.[109] Its significance was highlighted recently with the opening of a joint campus between Harbin and St Petersburg University as part of President Putin's state visit to China in May 2024.[110]

Figure 16: Top 5 institutions in *high-specification machining processes* (ranked by 21-year performance)



5. Advanced aircraft engines

*equal 5th position with Cranfield University, Johns Hopkins University and Northwestern Polytechnical University

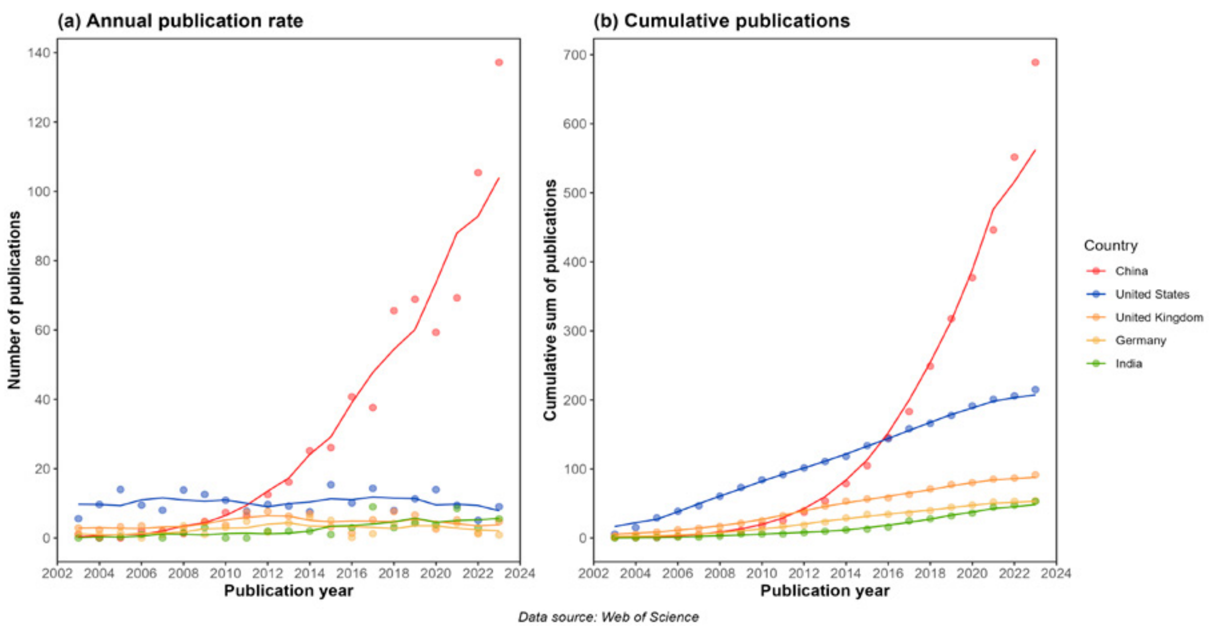
Advanced aircraft engines are new engine technologies that allow greater speed, stealth, range and fuel efficiency for aircraft, while reducing unit costs. To complement the development of 6th-generation fighter aircraft, current research efforts also include engines that can operate efficiently at a range of altitudes.[111] Electric propulsion systems are also an area of active research because of the new combat-support capabilities that such systems may enable.[112]

Country performance and projections

The US, UK and France leading in the 2003–2007 rankings mirrors the three countries' status as historically prominent countries in the aerospace industry.[113] From a research perspective, however, any changes in the high-impact publication rates over the 21-year period are dwarfed by China's rapid rise, which has accelerated over the past decade (Figure 17).[114]

The US, in contrast, maintained a steady rate throughout the period, as did Germany and the UK. While Germany and the UK managed to retain their positions near the top of the rankings (Germany placed 6th in 2019–2023), France fell considerably, now ranking 20th. India and Turkey showed a slight increase in publication rates in recent years, and consequently make the top 5 countries in the recent rankings. Both countries improved their position substantially from 2003–2007, at which point India was ranked 14th and Turkey 18th. Given the sensitivities—military and commercial—it's likely that a range of countries (for example, the US, China and European countries) have moved portions of their research in this field to classified and commercial-in-confidence labs.

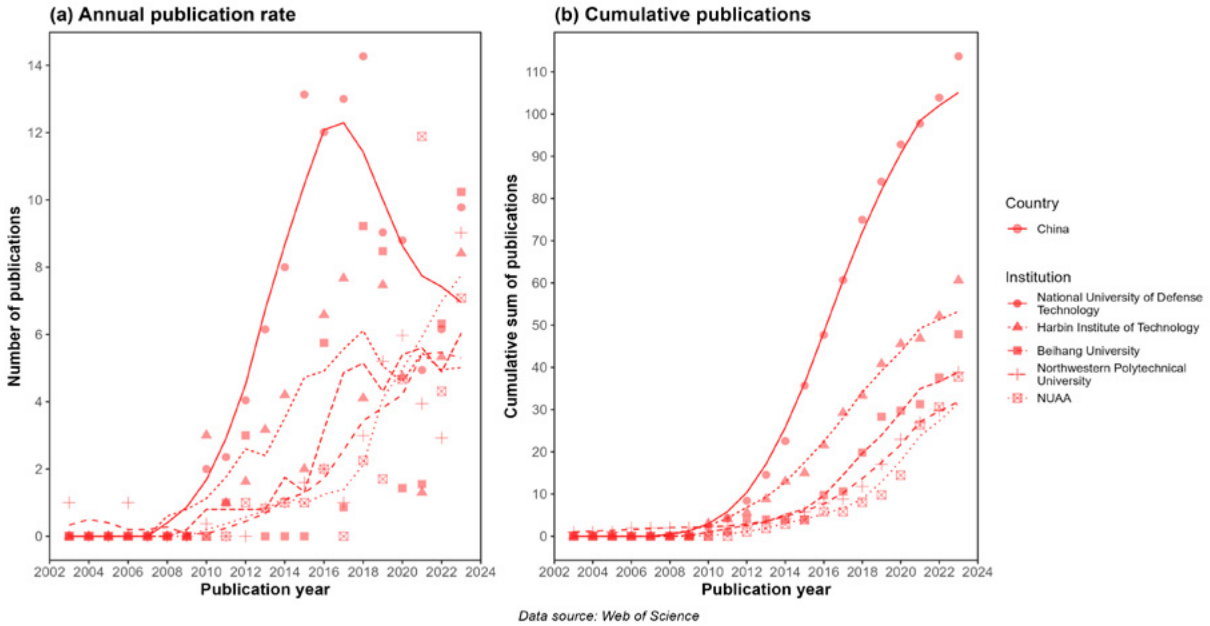
Figure 17: Top 5 countries in *advanced aircraft engines* (ranked by 21-year performance)



Institution performance

In 2003–2007, there was a noticeably higher concentration of government or government-affiliated institutions towards the top of the rankings – NASA and the US Air Force Research Laboratory included, which ranked 1st and 2nd respectively – reflecting this technology's clear relevance to military and space capability. All those institutions occupy much lower positions in the 2019–2023 rankings. In contrast, we now see China-based institutions dominate the recent rankings. The top-ranked institution in 2019–2023 is the PLA's premier institution for scientific research and education: the National University of Defense Technology (NUDT).[115] The other Chinese institutions in the top 5 are all part of the 'Seven Sons of National Defence', which is a group of universities deeply integrated with the Chinese military and defence industry.[116] The only universities not based in China that rank in the top 20 include the National University of Singapore (15), the UK's University of Nottingham (18) and the US's Purdue University System (20).

Figure 18: Top 5 institutions in *advanced aircraft engines* (ranked by 21-year performance)



6. Drones, swarming and collaborative robots

Institution rankings

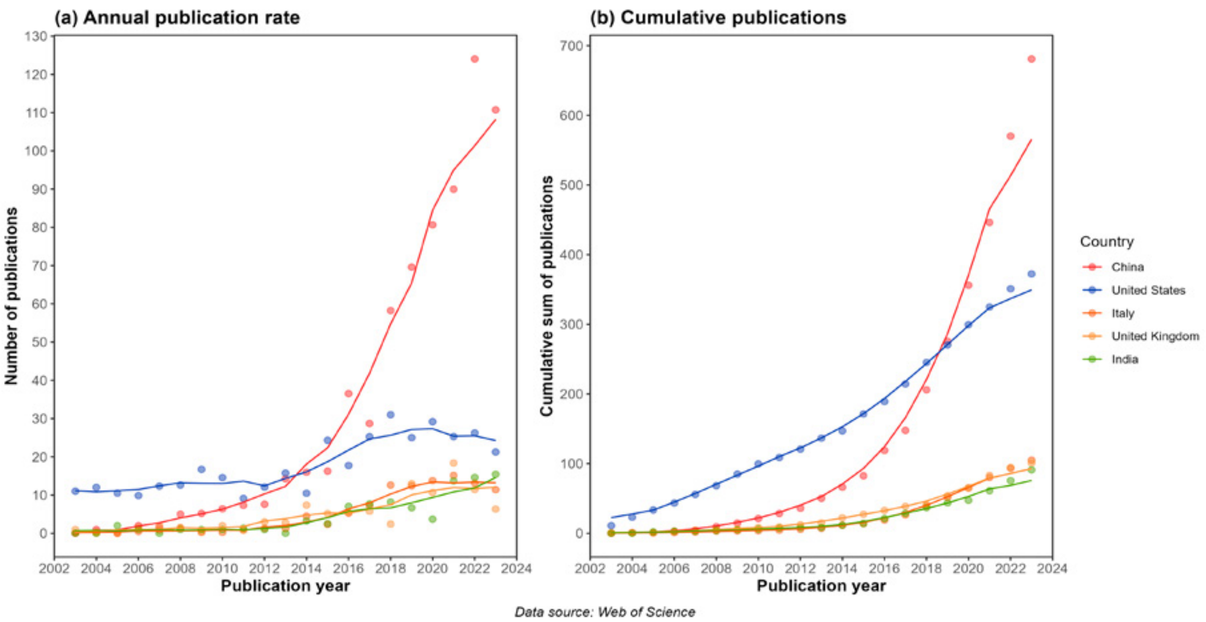
	2003-2007	2019-2023
1	École Polytechnique Fédérale de Lausanne (EPFL)	Beihang University
2	Free University of Brussels	Tsinghua University
3	University of Southern California	Wuhan University of Technology
4	Carnegie Mellon University	Beijing Institute of Technology
5	Middle East Technical University	Xidian University

Drones, swarming and collaborative robots are air, ground and sea vehicles that require limited human direction to achieve common goals. Initial research in this technology sought to mimic behaviours that scientists observed in self-organising systems, such as ant colonies, but recent innovations have focused on making collaborative systems that can function in real-world environments,[117] and with AI integration. As with many other defence technologies, actualising this technology is strongly dependent on a variety of other enabling technologies, such as *coatings*, *electric batteries*, *machine learning* and *mesh and infrastructure independent networks*.

Country performance and projections

Our data shows that the US once had an enormous historical lead in this technology: over 80% of all highly cited publications in 2003 came from US institutions. From 2003 to 2013, China steadily increased its high-impact publication rate, while the other top-ranking countries more-or-less plateaued (Figure 19). From 2013 onwards, there's been a notable bump in publication rates for all the top performers, but China's publication rate has surged. Consequently, the US's high-impact research share dropped to only 10% in 2023. A striking feature in the research landscape for this technology is how little overlap there is between the countries that ranked in the top 5 within each of the three time periods considered: the US is the only country in the top 5 across the three time periods. This is perhaps best reflected in Switzerland, which ranked 2nd in 2003–2007 but fell to 20th in 2019–2023. The volatility within the rankings suggests a large spread in research output growth among countries over the 21-year period. China is currently leading in this technology and bridged the gap with the US in cumulative publications in 2019. It is worth noting the presence of Iran in 4th place for the intermediate period (2011-2015). Iranian drones have featured prominently in recent news with their deployment in the Russian invasion of Ukraine.[118] There is growing global interest in Iranian drones for combat purposes.[119]

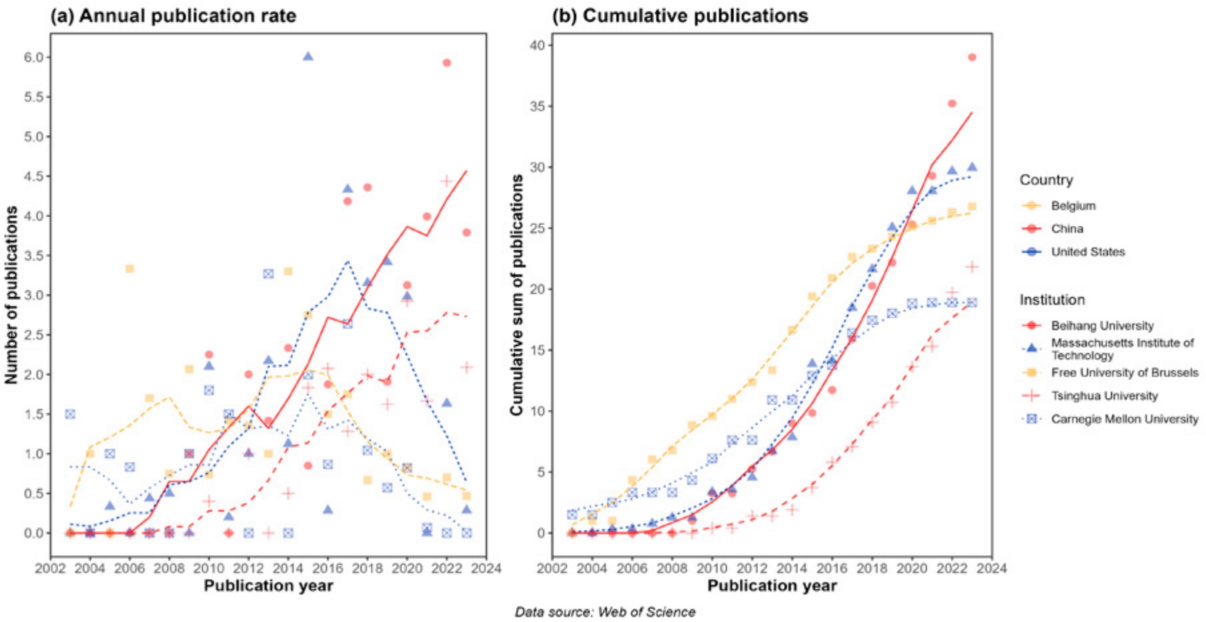
Figure 19: Top 5 countries in *drones, swarming and collaborative robots* (ranked by 21-year performance)



Institution performance

The difference between historical performance and recent performance is very prominent in this technology. Indeed, most institutions saw their ranking change considerably over the 21-year period, mirroring the volatility seen in the country rankings. While in 2003–2007 we see institutions from Switzerland, Belgium, the US and Turkey in the top 5, by 2019–2023 all the top 5 institutions are based in China. Indeed, there are only two institutions in the top 10 (recent performance) not based in China: Sweden's KTH Royal Institute of Technology and Iran's Islamic Azad University.

Figure 20: Top 5 institutions in *drones, swarming and collaborative robots* (ranked by 21-year performance)



7. Electric batteries

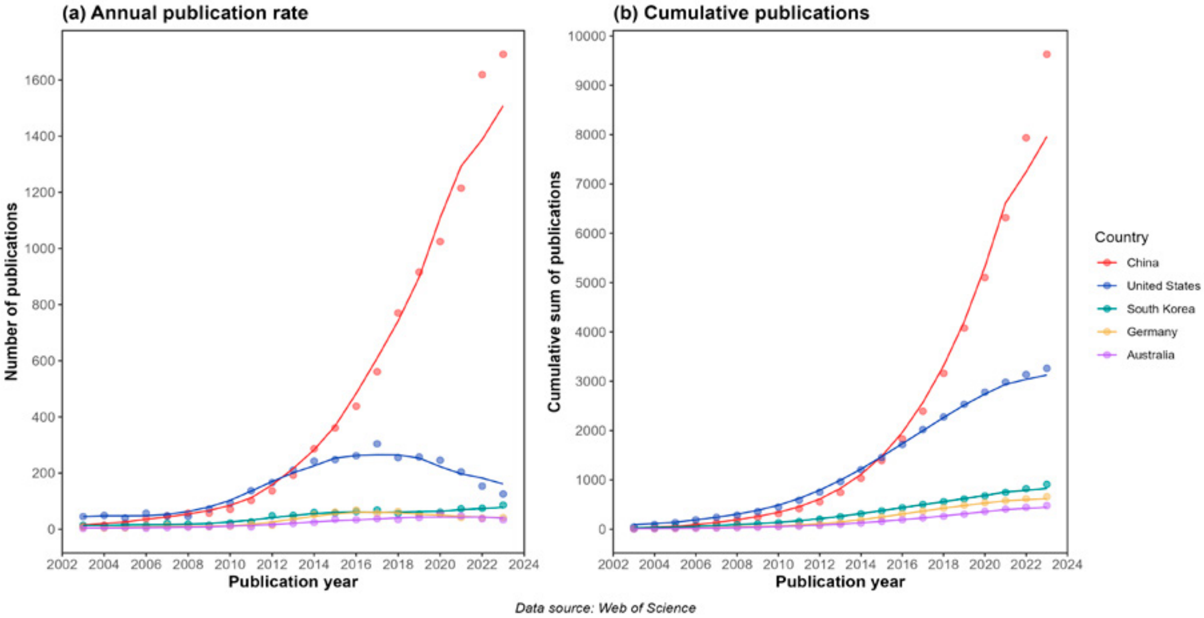
Electric batteries are devices that store electrochemical energy over multiple charge–discharge cycles. While research in this area was initially directed towards improving consumer products such as smartphones, recent work has focused more on improving energy density to make batteries more suitable for high-power uses such as in EVs or as part of renewable-energy grids.[120]

Country performance and projections

China's lead in *electric batteries* research is stunning and is perhaps the most pronounced high-impact research advantage China holds out of the 64 critical technologies in the *Critical Technology Tracker*. While 30% of highly cited research was conducted in the US in 2003, that proportion plummeted to 5% by 2023, while China's contribution grew from 10% in 2003 to a staggering 75% in 2023. While the US managed to keep pace with China before 2012, probably due to support by government investment in local battery manufacturers in 2009,[121] the US and China dramatically diverged from 2013 onwards.[122] China's surge corresponded with its government more clearly identifying advances in batteries as an important or strategic need in key planning documents.[123]

The US's contribution, in contrast, has declined, although not as sharply as China's gains (Figure 21). It could be overtaken soon by South Korea, although the Biden administration has taken steps to support American battery manufacturing, including investments in R&D.[124] China's current high-impact research lead in *electric batteries* is matched by its prominent role in global battery manufacturing capacity: six out of the top 10 EV battery manufacturers are reported to be Chinese companies, of which CATL and BYD lead the way.[125]

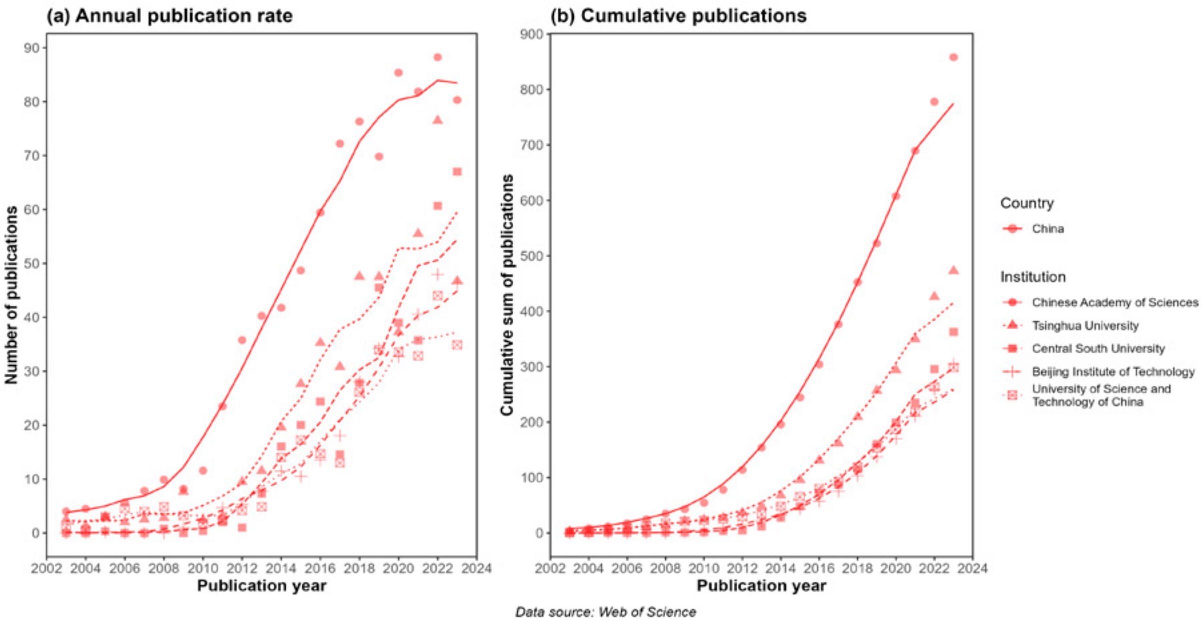
Figure 21: Top 5 countries in *electric batteries* (ranked by 21-year performance)



Institution performance

Beyond CAS, which is the leading institution in both historical and recent research performance, the leading institutions in *electric batteries* have changed considerably over the 21-year period. Major US research institutions such as the Argonne National Laboratory, University of California Berkeley and MIT, each of which has a history of groundbreaking research, have been displaced by Chinese universities of increasingly global importance. In fact, recent performance suggests that there are only three institutions in the top 30 that are not based in China. They are the University of Texas at Austin (14), Stanford University (23) and the Helmholtz Association of German Research Centres (27).

Figure 22: Top 5 institutions in *electric batteries* (ranked by 21-year performance)



8. Photovoltaics

Institution rankings

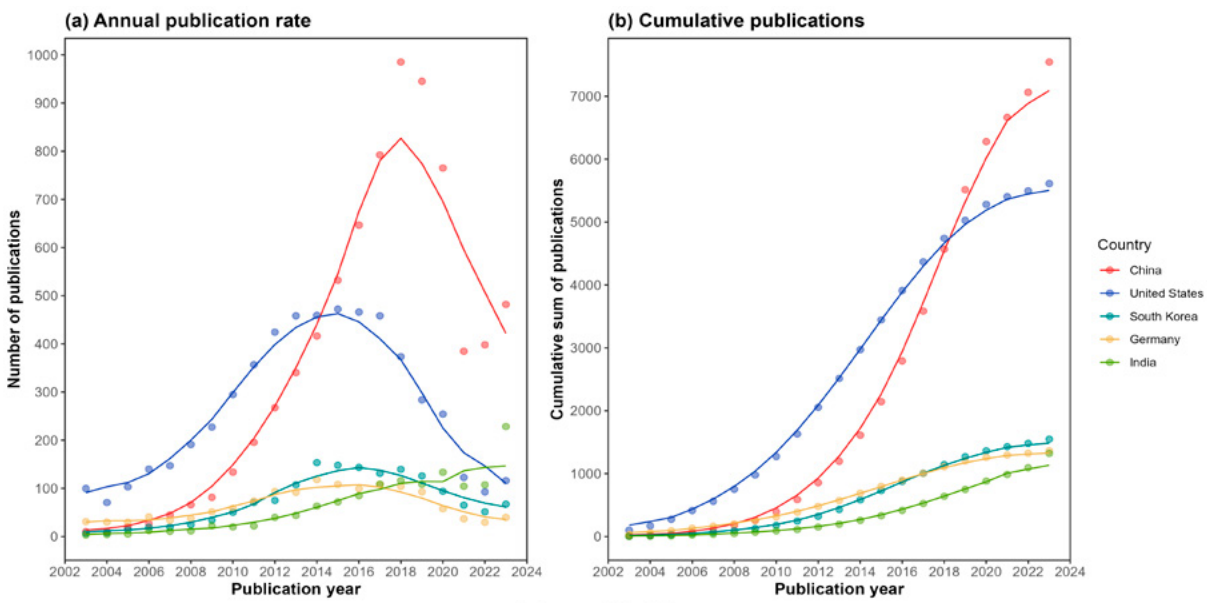
	2003-2007	2019-2023
1	École Polytechnique Fédérale de Lausanne (EPFL)	Chinese Academy of Sciences
2	National Renewable Energy Laboratory	Zhejiang University
3	Imperial College London	Huazhong University of Science and Technology
4	Chinese Academy of Sciences	North China Electric Power University
5	University of California Berkeley	South China University of Technology

Photovoltaics (PV) are semiconductor technologies that convert solar energy into electricity. While solar cells were first used in space applications,[126] current applications for PV are more ground-based and include low-emissions power stations, rooftop solar power and personal electronics. Over the past two decades, the price of PV has undergone a 15 times reduction, making it cheaper than coal and accelerating its widespread adoption from initially niche applications.[127]

Country performance and projections

There's a remarkable correlation between the *Critical Technology Tracker*'s dataset for *photovoltaics* and changes in the manufacturing sector in the past two decades.[128] In the early 2000s, the US was the leading PV manufacturer and the top publisher of highly cited publications in PV, bolstered by government funding in 2003.[129] Similarly, Japan and Germany were the 2nd- and 3rd-ranked countries in both PV manufacturing and highly cited publications. China's share of global PV research made a steady climb past those three countries, while its share of the global PV industry continued to grow through the 2007–08 global financial crisis (when the US private sector took a hit) and the end of government subsidies in Japan and Germany.[130] In our data, South Korea's research performance in PV has been enough to overtake both Germany and Japan in the past two decades (Figure 23(a)). While India came 3rd over the past five years, it remains on an upward trajectory, and it exceeded the US in high-impact research outputs in 2022.[131]

Figure 23: Top 5 countries in *photovoltaics* (ranked by 21-year performance)

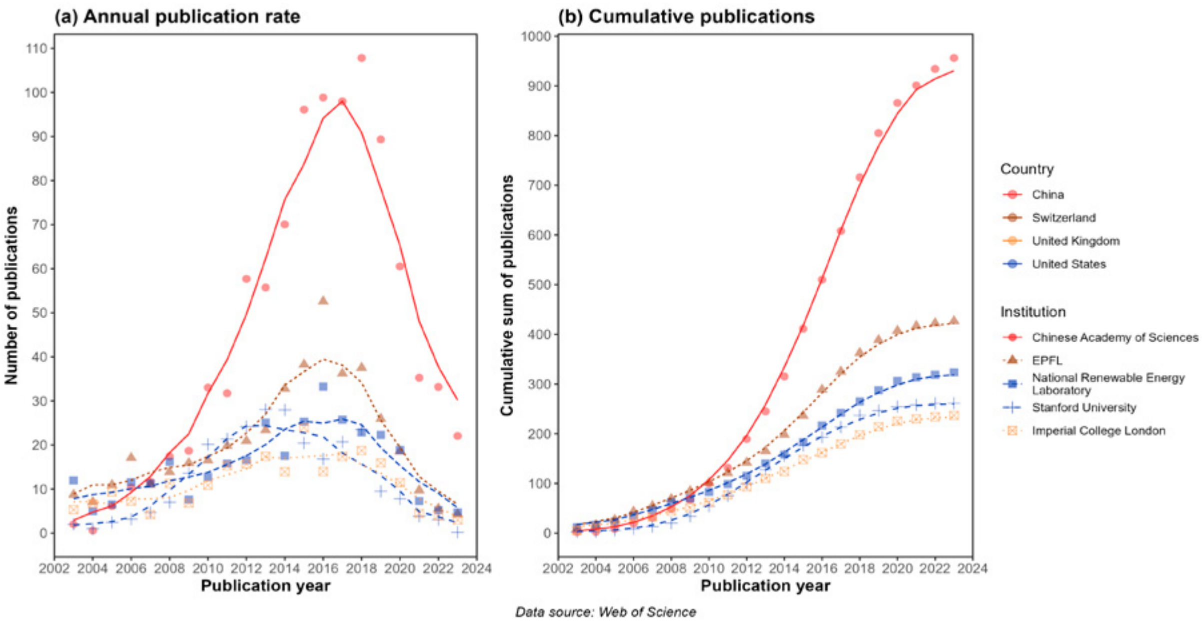


Data source: Web of Science

Institution performance

In the early 2000s, the top-performing institutions were the Federal Institute of Technology of Lausanne (EPFL) and the US National Renewable Energy Laboratory,[132] while Imperial College London occupied a clear 3rd position. CAS has managed to swiftly catch up to those pioneering institutions in this technology, and by 2013 had the highest share of cumulative publications in the field (Figure 24(b)). While the historical data shows that the top 5 institutions are from a diversity of countries, the top 5 institutions ranked from their research performance in the past five years show a dominance of China-based institutions.[133]

Figure 24: Top 5 institutions in *photovoltaics* (ranked by 21-year performance)



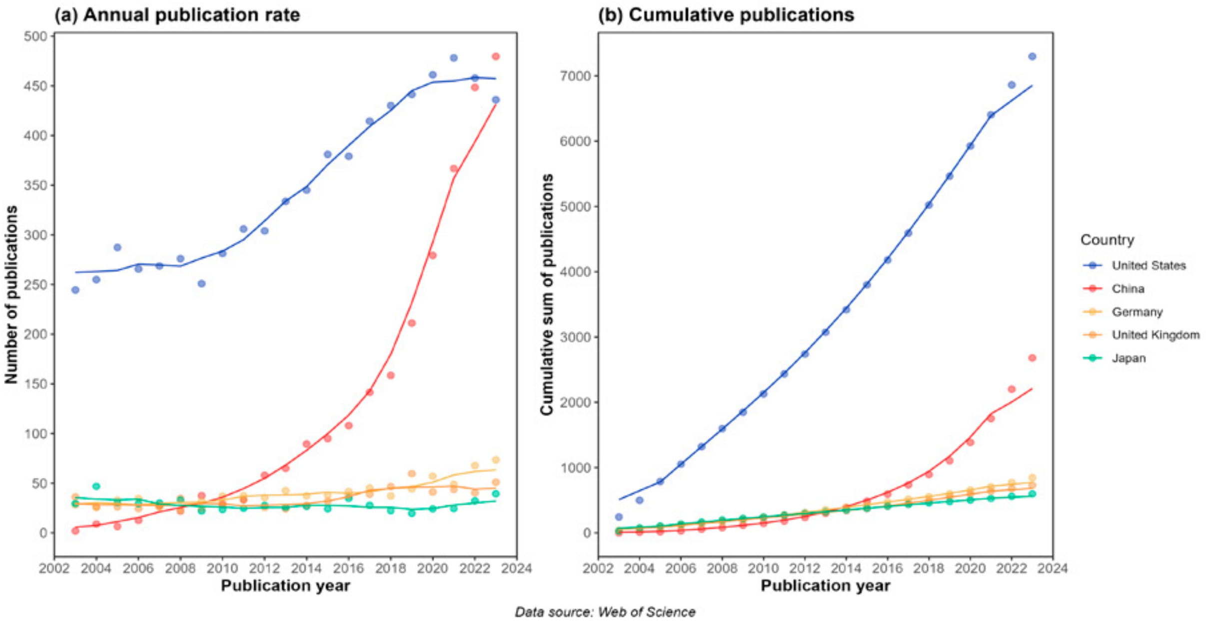
9. Genetic engineering

Genetic engineering describes the set of techniques used to intentionally manipulate genetic material for useful or beneficial purposes. Various gene-editing tools (such as CRISPR-Cas9 technologies) were developed in the 2000s, and many of today's innovations have continued to build on those advances.[134] Research has focused on applying tools to selectively modify the genes of humans, plants, animals and bacteria for a wide variety of applications, such as treating illness and making crops more resilient to climate change.[135] The use of gene-editing tools in this technology is fraught with ethical issues, especially when applied to the human genome.

Country performance and projections

The US had a leading and constant high-impact publication rate, accounting for over 50% of publications each year in *genetic engineering* research, until 2010. The 21-year graph (Figure 25) then shows a rapid increase in the US's publication rate from 2012, but at a much slower rate compared to China's, which has grown exponentially over the past decade. It must be noted that it was in 2012 that the CRISPR-Cas9 gene-editing tool showed that Cas9 provided a revolutionary way to scissor specific DNA strands and opened up many new opportunities in gene editing.[136] As of 2022, the US and China reached parity in their publication rates; each country claimed 30% of global research. Germany and the UK appear to have moderately increased their publication rates over the 21-year period, while Japan's has been stable. In the rankings, however, we see that Japan's stable publication rate has dropped from 2nd to 5th place, while Germany and the UK have managed to maintain their 3rd and 4th positions, respectively. Our projections show that, based on current trajectories, China is unlikely to surpass the US in cumulative publications any time soon.

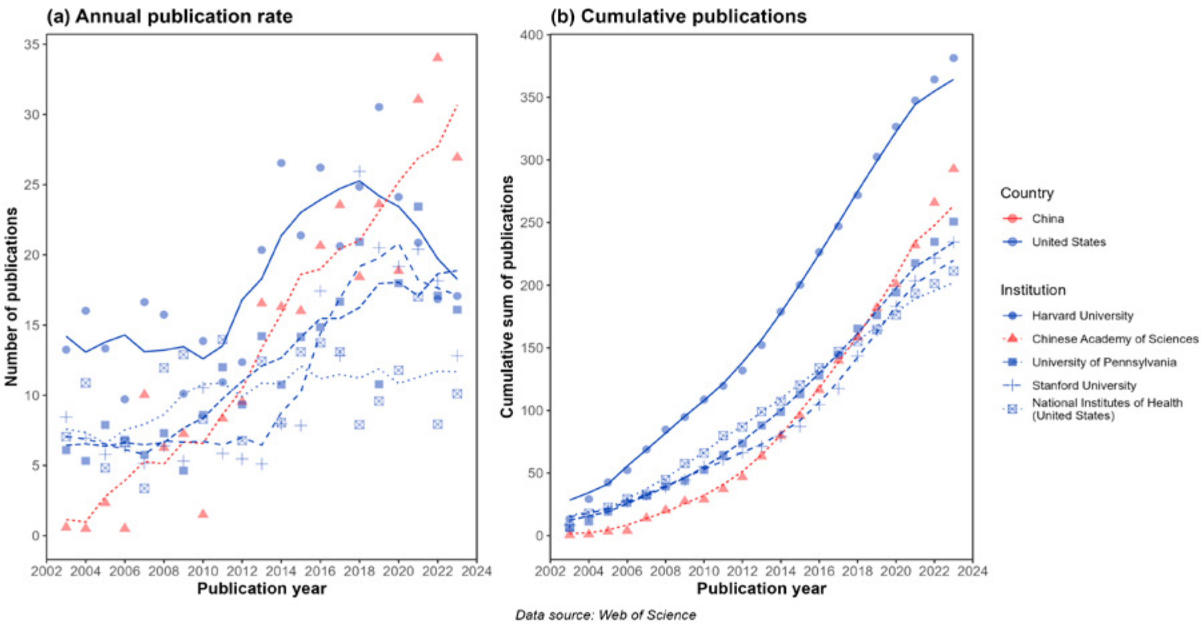
Figure 25: Top 5 countries in *genetic engineering* (ranked by 21-year performance)



Institution performance

The trends in the top 5 institutions generally match the national trends (Figure 26). US-based institutions, which initially led, produced a moderate increase in high-impact publications from the early 2010s, while CAS and the Chinese Academy of Agricultural Sciences rose in strength throughout that period. In recent years, CAS has surpassed its American peers in its publication rate and now, over the most recent five-year period, has published the most high-impact research in *genetic engineering*. Within the US itself, however, the leading institutions have remained fairly consistent over the 21 years: Harvard University, Stanford University and the University of Pennsylvania are in both the 2003–2007 and 2019–2023 top 5.

Figure 26: Top 5 institutions in *genetic engineering* (ranked by 21-year performance)



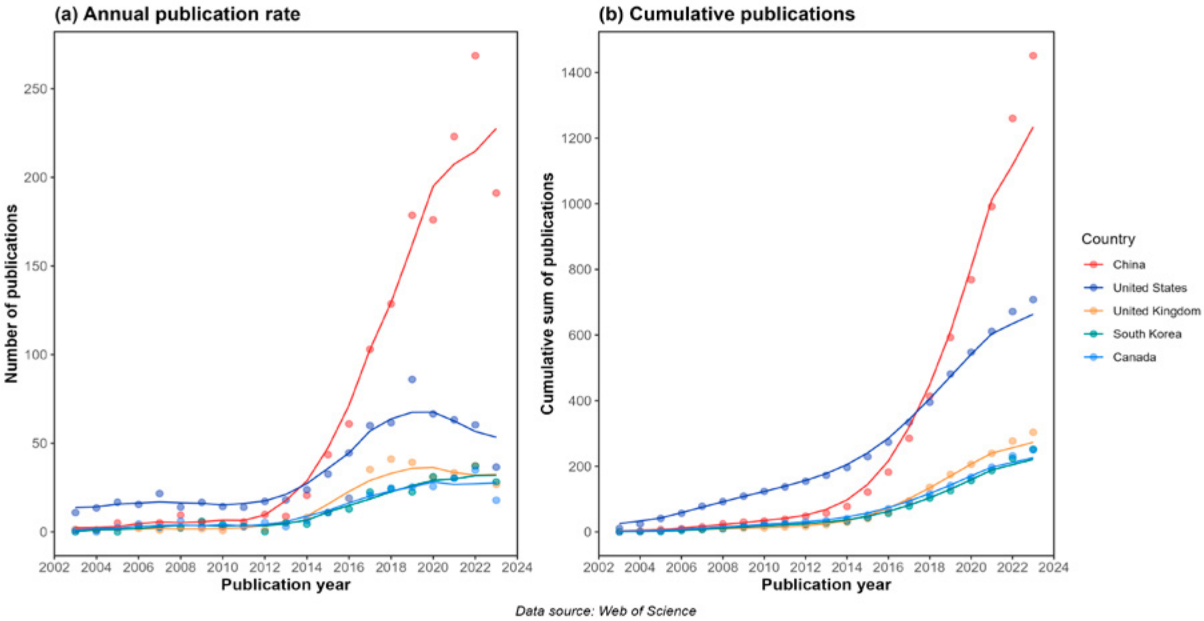
10. Advanced radiofrequency communication

Advanced radiofrequency communication technologies enable the wireless transfer of information. The 3rd generation of mobile communication technologies began its rollout in the early 2000s and laid the foundation for mobile high-speed data with applications such as GPS and video-on-demand.[137] It has since been replaced by 4G and 5G systems, and 6G is expected to start deployment around 2030. Current research in this field is directed towards the next generation of wireless communication networks. Research in recent years has also seen improvements in the energy efficiency of those systems, enabling new applications in areas such as space-based communications.[138]

Country performance and projections

The US initially had a comfortable lead in this technology, accounting for just under 50% of research in 2003. Over the 21-year period, however, China rapidly increased its publication rate, surpassing the US in 2015. In fact, from 2013, we've seen an increased high-impact publication rate for all the top-ranking countries (Figure 27(a)), which coincided with global efforts to advance innovation in 5G communication networks.[139] However, other countries have struggled to keep up with China's efforts; subsequently, the US's and the UK's shares of high-impact publications fell to just 5% in 2023, and South Korea and Canada were close behind them. While Canada, a strong early performer, just slipped out of the 2019–2023 top 5 rankings and into 6th place, Germany's slump was more prominent with the country now ranking 12th.

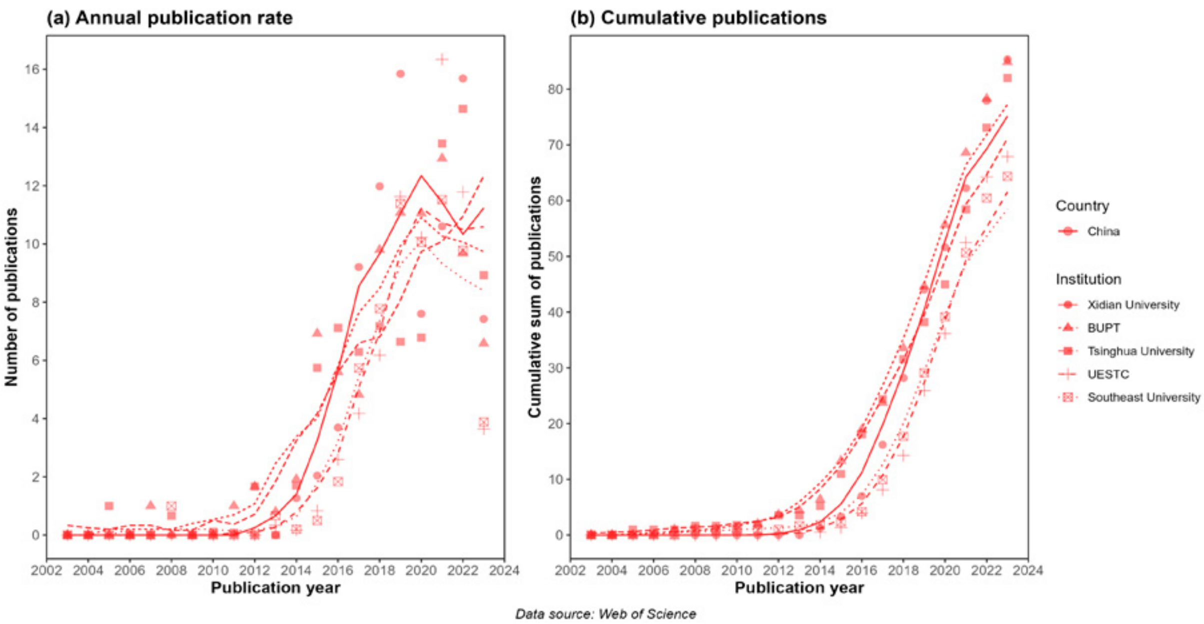
Figure 27: Top 5 countries in *advanced radiofrequency communication* (ranked by 21-year performance)



Institution performance

The top 5 institutions ranked from their performance between 2019 and 2023 have had a remarkably similar publication-rate trend over the 21-year period (Figure 28). Notably, none of them were driving research in the 2000s, but they rapidly accelerated their high-impact publication rates from 2012 onwards. The highest ranked US-based institution between 2003 and 2007, the Georgia Institute of Technology, is still a strong performer overall, ranking 7th based on its performance between 2019–2023. That's still, however, a significant drop from 2004, when this single institution was responsible for almost 20% of research conducted in that year. Samsung in the 2003–2007 rankings is one of the very few non-US-headquartered companies that place within the top 5 institutions. Xidian University[140], which is the lead institution in the recent performance ranking, sits under China's Ministry of Education but it is also jointly supervised by the government's defence industry agency (the State Administration of Science, Technology and Industry for National Defense) and by one of the country's state-owned defence companies, China Electronics Technology Group Corporation (CETC).[141] CETC specialises in defence electronics and technology and has seen a number of its subsidiaries (and its chip technology) sanctioned by the US and Japanese governments.[142]

Figure 28: Top 5 institutions in *advanced radiofrequency communication* (ranked by 21-year performance)



Conclusion

With 21 years of data now available on the 64 technologies in the *Critical Technology Tracker*, the most striking finding is just how dramatically the research race between major powers can drastically change in less than a generation. That, in turn, points to the considerable returns that can be yielded by a coordinated and well-resourced national effort—and the converse risks, especially for pioneering S&T powers, in allowing R&D to fall away as other countries are surging.

As our data shows, China has made huge strides over the past two decades, and especially since the 2010s. Right in the middle of that pivotal decade, in 2015, Beijing announced its 'Made in China 2025' plan, which included massive direct state funding for R&D in key technologies. Beijing's strategic investment in S&T was already underway, but that plan established the level of ambition that the Chinese Government had for technological supremacy—a determination that hasn't abated since then. This year alone, China has planned a major boost to its annual budget for S&T, increasing it to US$51.5 billion (¥370.8 billion). Focused on 'basic research, applied basic research, and national strategic science and technology tasks', that amounts to a 10% increase from 2023.[143] China's investments go far beyond research: large and complementary investments are being made into industry policy, upgrading supply chains and the manufacturing sector.[144]

The fact that China has enhanced its lead since last year's *Critical Technology Tracker* results, especially in defence technologies, points to its growing momentum in S&T, which other countries would be wise to assume will continue.

For some technologies, this has occurred because the high-impact research output of pioneering S&T powers such as the US, Japan, the UK and Germany has flatlined, putting them in a position where they're losing—or at risk of losing—some of the research and scientific strengths they have built over many decades. Some of these long-term changes can be seen, for example, in the dwindling numbers of globally recognised (and sometimes Nobel Prize winning) R&D laboratories based in electronics and telecommunications firms across Europe and the US.[145] Equally interesting and more recent trends include India's advances in the rankings, and a corporate resurgence within the *Tracker's* institutional results, led by US technology companies that are especially strong in AI.

With other technologies, however, this shift that can be seen across the 21-year dataset is not due to a decrease in high-impact research activity by those pioneering S&T powers, but is instead being driven by an enormous surge in China's research outputs over the past 21 years. China has executed a dramatic step-up in S&T research performance that other countries simply haven't been able to match.

The historical strong performance of the US and other advanced economies in high-impact research is reflected in their sustained vitality. For example, the US's continued innovation and current leadership in key technology areas amidst immense competition, especially in *quantum computing* and *vaccines and medical countermeasures*, shows their long-term strengths across the full spectrum of the technology ecosystem. Decades of research effort can lead to decades of payoff in the application and commercialisation of the knowledge and expertise that they've built up. High-impact research is a predictor and leading indicator of a strong and innovative economy. However, those payoffs will end and momentum will eventually falter without ongoing investments in scientific research, which is why the immense economic power epitomised by places such as Silicon Valley shouldn't be taken for granted. Some observers might argue that China's ascendance into an S&T research power—indeed *the* research power—doesn't matter because other countries, the US in particular, remain ahead in commercialisation, design and manufacturing. That might be true for some technologies, but it represents a very short-term attitude. China, too, is making enormous investments in its manufacturing capabilities, it is also subsidising key industries and achieving technological breakthroughs that are catching the world by surprise.[146]

Measuring high-impact research, by itself, doesn't provide a full picture of a country's current technological or innovation competitiveness. The purpose of the *Critical Technology Tracker* is not to assess the current state of play but to improve global understanding of countries' strategic intent and potential future S&T capability.

Our results serve as a reminder to governments around the world that building technological capability takes a sustained investment in, and accumulation of, knowledge, innovative skill, talent and high-performing institutions—none of which can be acquired through only short-term investments. Strategic investments are needed in technologies that are identified as important to a country's national interest. Continuous investments in those technology areas must then follow. And, of course, that must take place alongside complementary efforts that help build capability across the S&T life cycle: targeted policies on issues such as skilled migration, industry reform and incentives to boost innovation, manufacturing capability and commercialisation opportunities.

Given the extent to which strategic influence will be determined by technological primacy, even the US has demonstrated that it needs trusted partners in research, innovation and industry to maintain an edge over major competitors such as China.

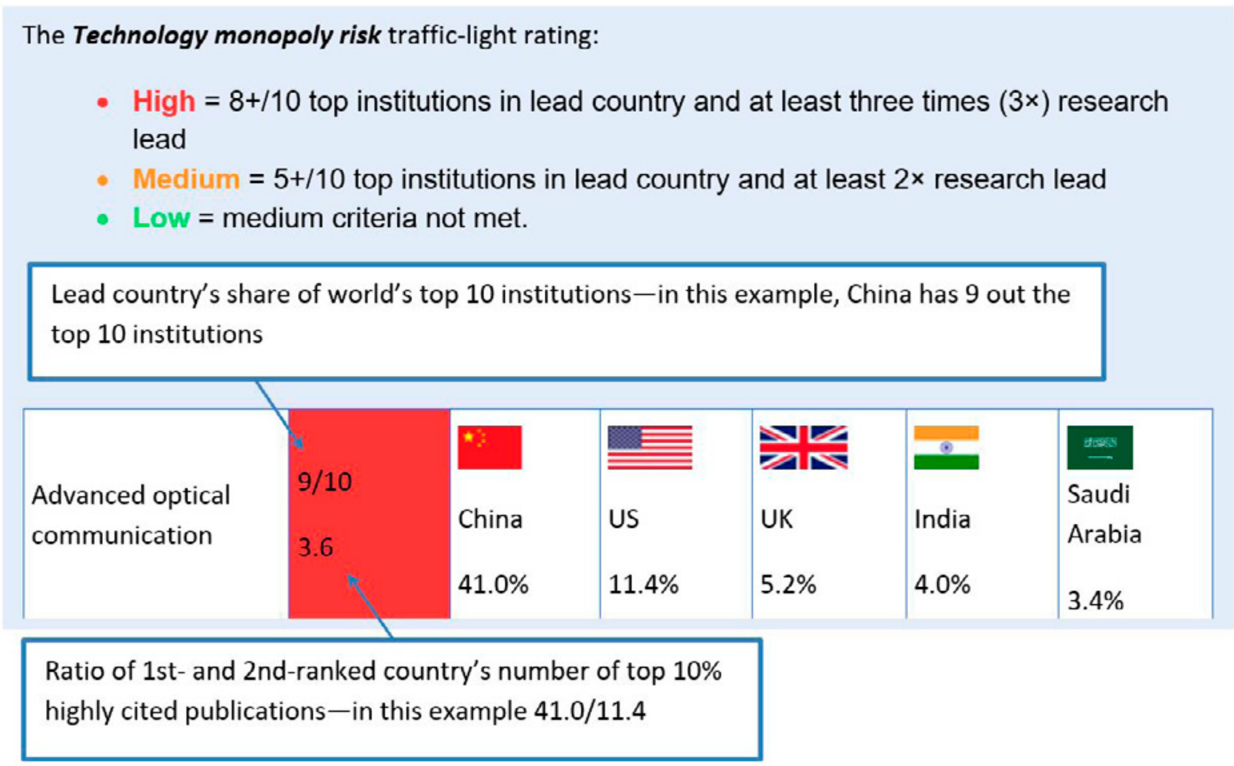
In our 2023 report, we made 23 recommendations, all of which remain relevant for countries today.[147] Grouped into four themes, those recommendations call for partners and allies to 1) boost investment, drive commercialisation and build talent pipelines; 2) enhance global partnerships; 3) supercharge intelligence efforts; and 4) consider moonshots (big ideas), including long-term funding via sovereign wealth funds for research, development and technology innovation. Without bigger changes to the status quo, the trajectory laid out in this report will continue to be consolidated.

The *Tracker* results show that countries can benefit from cooperation on technology by pooling their efforts and finding complementary and tangible areas in which to collaborate in an era when S&T expertise is becoming increasingly concentrated in one country. Planning and acting more strategically and more ambitiously, including by making the most of combined strengths, might be the only way to stay collectively ahead.

Appendix 1: Top 5 countries visual snapshot (2019–2023)

Below is a visual snapshot showing the top 5 countries ranked by their proportion (%) of high-impact research outputs across 64 technologies over the five years from 2019 to 2023. On the left-hand side is a column headed *Technology monopoly risk* that highlights concentrations of scientific and technological research expertise in a single country. A high *technology monopoly risk* is a potential indicator for future breakthroughs in technology capability. This metric is a combination of two factors:

1. the lead country's share of world's top 10 institutions
2. the lead country's lead over its closest competitor (ratio of top 10% publications).



Advanced information and communication technologies

Technology	Tech monopoly risk	Top 5 countries				
Advanced optical communication	9/10 3.6	41.0%	11.4%	5.2%	4.0%	3.4%
Advanced undersea wireless communication	9/10 6.1	51.5%	8.5%	7.7%	5.7%	3.5%
Advanced radiofrequency communication	6/10 3.3	31.9%	9.6%	5.6%	5.2%	4.6%
Distributed ledgers	7/10 2.9	29.4%	10.0%	9.5%	5.7%	4.7%

High-performance computing	6/10 1.3	30.6%	23.7%	8.1%	4.1%	4.0%
Mesh and infrastructure-independent networks	6/10 1.8	29.2%	16.3%	7.3%	3.9%	3.1%
Protective cybersecurity technologies	4/10 1.6	22.1%	13.7%	7.9%	5.9%	5.0%

Advanced materials and manufacturing

Technology	**Tech monopoly risk**	**Top 5 countries**				
Advanced composite materials	9/10 4.1	45.4%	11.2 %	6.2%	4.1%	4.0%
Advanced protection	8/10 3.4	43.5%	12.9%	4.8%	4.1%	2.9%
Coatings	10/10 11.6	62.5%	5.4%	5.3%	3.0%	2.8%
High-specification machining processes	9/10 3.4	42.8%	12.6%	10.6%	3.5%	3.0%
Nanoscale materials and manufacturing	10/10 11.2	60.6%	5.4%	5.2%	4.0%	3.6%
Novel metamaterials	9/10 4.0	51.7%	12.8%	4.2%	3.4%	2.7%
Smart materials	9/10 6.0	46.1%	7.7%	6.2%	5.2%	3.3%
Advanced explosives and energetic materials	6/10 2.9	53.0%	18.1%	4.4%	3.6%	3.2%
Advanced magnets and superconductors	5/10 2.2	33.3%	15.0%	7.4%	6.8%	5.2%
Continuous-flow chemical synthesis	5/10 2.3	29.1%	12.8%	5.2%	4.6%	4.1%
Critical minerals extraction and processing	7/10 3.9	42.0%	10.7%	5.1%	2.6%	2.3%
Wide and ultrawide bandgap semiconductors	6/10 2.4	42.6%	17.6%	6.1%	4.9%	4.1%
Additive manufacturing	6/10 1.4	24.6%	18.0%	5.9%	5.0%	4.5%

Artificial intelligence, computing and communications

Technology	Tech monopoly risk	Top 5 countries				
Advanced data analytics	9/10 2.3	33.2%	14.4%	5.4%	4.0%	3.6%
AI algorithms and hardware accelerators	6/10 2.2	30.9%	14.0%	5.9%	5.0%	4.5%
Machine learning	9/10 2.4	36.5%	15.4%	5.4%	3.6%	3.2%
Advanced integrated circuit design and fabrication	4/10 1.1	24.4%	22.5%	5.6%	4.3%	4.2%
Adversarial AI	7/10 1.6	31.1%	19.5%	5.5%	5.1%	3.5%
Natural language processing	6/10 1.0	24.8%	24.1%	4.2%	4.2%	3.7%

Biotechnology, gene technologies and vaccines

Technology	Tech monopoly risk	Top 5 countries				
Synthetic biology	10/10 4.4	57.7%	13.1%	2.7%	2.6%	2.6%
Biological manufacturing	9/10 2.8	28.5%	10.3%	8.5%	3.3%	3.0%
Novel antibiotics and antivirals	6/10 2.6	29.7%	11.6%	11.3%	5.5%	4.2%
Genetic engineering	6/10 1.3	37.0%	29.0%	4.7%	3.8%	2.3%
Genomic sequencing and analysis	9/10 1.6	35.6%	22.2%	3.9%	3.9%	2.6%
Nuclear medicine and radiotherapy	4/10 1.3	27.1%	21.1%	6.3%	5.5%	4.7%
Vaccines and medical countermeasures	7/10 1.9	26.4%	14.0%	6.0%	5.9%	5.2%

Defence, space, robotics and transportation

Technology	Tech monopoly risk	Top 5 countries				
Advanced aircraft engines	10/10 9.0	63.1%	7.0%	3.6%	3.0%	3.0%
Drones, swarming and collaborative robots	8/10 3.7	38.4%	10.3%	5.3%	4.8%	4.4%
Hypersonic detection and tracking	10/10 5.5	72.9%	13.2%	3.3%	1.5%	1.3%
Advanced robotics	7/10 1.8	34.5%	19.7%	4.7%	4.2%	4.0%
Autonomous systems operation technology	7/10 1.9	34.3%	18.4%	4.8%	4.5%	3.7%
Small satellites	4/10 1.3	23.0%	17.9%	9.2%	4.0%	3.8%
Space launch systems	5/10 1.2	22.8%	19.0%	7.2%	6.5%	6.4%

Energy and environment

Technology	Tech monopoly risk	Top 5 countries				
Electric batteries	10/10 6.6	68.3%	10.4%	3.7%	2.4%	2.3%
Hydrogen and ammonia for power	9/10 11.1	60.8%	5.5%	5.1%	3.3%	2.6%
Supercapacitors	9/10 8.1	62.9%	7.8%	6.0%	3.6%	1.9%
Directed energy technologies	7/10 2.7	43.7%	16.4%	5.2%	4.6%	3.2%
Nuclear waste management and recycling	7/10 3.2	42.8%	13.3%	5.4%	4.9%	3.7%
Photovoltaics	7/10 3.4	31.1%	9.1%	7.1%	4.2%	3.3%
Biofuels	6/10 1.4	23.4%	16.7%	4.7%	4.4%	3.6%
Nuclear energy	5/10 1.7	31.6%	18.6%	5.2%	5.1%	4.3%

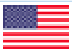
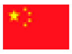
Quantum technologies

Technology	Tech monopoly risk	Top 5 countries				
Post-quantum cryptography	6/10 2.8	33.9%	12.1%	5.6%	5.1%	5.1%
Quantum computing	7/10 2.1	33.6%	15.9%	5.8%	5.7%	3.7%
Quantum communication	6/10 2.0	33.6%	16.8%	7.3%	6.0%	3.8%
Quantum sensors	2/10 1.0	24.1%	23.8%	7.7%	4.3%	4.1%

Sensing, timing and navigation

Technology	Tech monopoly risk	Top 5 countries				
Inertial navigation systems	9/10 4.5	48.5%	10.9%	3.9%	3.7%	3.6%
Multispectral and hyperspectral imaging sensors	9/10 5.5	53.7%	9.8%	3.7%	3.5%	2.7%
Photonic sensors	10/10 4.0	45.8%	11.4%	5.4%	3.8%	3.0%
Radar	10/10 3.4	42.7%	12.7%	5.1%	3.6%	3.2%
Satellite positioning and navigation	8/10 3.4	40.9%	12.2%	4.5%	4.2%	3.5%
Sonar and acoustic sensors	10/10 3.5	49.5%	14.3%	4.3%	4.1%	3.2%
Magnetic field sensors	6/10 2.1	35.2%	16.6%	7.7%	7.0%	4.6%
Atomic clocks	6/10 1.5	29.5%	19.4%	9.5%	7.3%	5.2%
Gravitational-force sensors	5/10 1.0	20.9%	20.8%	7.3%	6.4%	5.7%

Unique AUKUS-relevant technologies

Technology	Tech monopoly risk	Top 5 countries				
Autonomous underwater vehicles	10/10 10.3	 66.8%	 6.5%	 3.3%	 2.2%	 2.1%
Electronic warfare	10/10 4.2	 51.5%	 12.3%	 4.1%	 2.9%	 2.8%
Air-independent propulsion	7/10 5.1	 44.0%	 8.6%	 7.1%	 4.3%	 3.8%

Appendix 2: Detailed methodology

What is our data source?

Research publication data covering the years 2003 to 2023 was downloaded from the Web of Science (WoS) Core Collection database.[148] WoS Core Collection was selected because it's heavily used by researchers who study scientific trends and it has well-understood performance characteristics.[149] The dataset included conference and journal publications and excluded bibliographic records that were deemed to not reflect research advances, such as book reviews, retracted publications and letters submitted to academic journals.[150]

In addition, we used data from the Research Organization Registry (ROR)[151] to clean institution names, and data from the Open Researcher and Contributor ID (ORCID)[152] database to build career profiles for the researchers plotted in the ASPI *Talent Tracker.*

What is a citation?

When a scientific paper references another paper, that's known as a citation. The number of times that a paper is cited reflects the impact of that paper within its field. Earlier publications typically have higher citation counts since they have had longer to accumulate citations, so only papers of a similar age should be compared using citation counts. We accounted for this by comparing only papers published in the same year by their number of citations.

What do we mean by high-impact research?

Distinguishing innovative and high-impact research papers from low-quality papers is critical when estimating the current and future technical capability of countries. Not all of the millions of research papers published each year represent valuable or useful scientific or technological progress, especially as academics and researchers are (often unrealistically) expected to publish multiple papers each year for their career progression. In our report, we define a highly cited paper as one that has a citation count in the top 10% of all the papers published in that year. There are certainly limitations to defining quality in this way but analysing 6.8 million unique research papers requires some concessions to be made to assess the aggregated high-impact research performance of countries and institutions.[153]

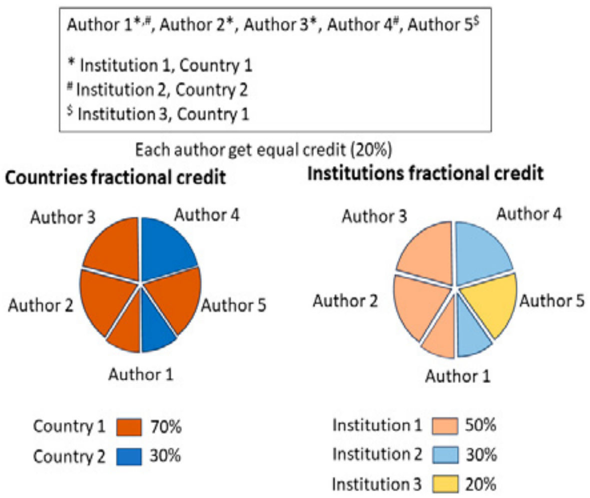
While citations are used as a quality metric in assessing research impact, citations are also an indicator of activity and interest. Scientific innovation is often disputed and contested, and this contestability, plays a key quality control function in the scientific community. However, given the importance of collaboration in scientific research, citations are also subject to being potentially influenced, consciously or unconsciously by an author's professional networks (sometimes this is referred to as 'clubbing'). While there can be valid reasons for this phenomenon to exist, for example scientists in a small field may be more likely to cite who they have worked with or who they regularly see at conferences and networking events, this factor can potentially boost citations. There are studies that quantify whether papers are more (or less) likely to be cited by scientists in the same country as the authors' country.[154] Such efforts to potentially boost citation counts is one of the reasons why we selected the WoS (core collection), which has strict editorial selection and evaluation processes,[155] and is also why we deliberately disregarded some datasets, such as the Russian Science Citation and the Chinese Science Citation databases.

How did we count research papers?

Each paper in our WoS dataset includes the address of the institution that each author is affiliated with. The obvious way to assign credit to each country or institution is to count the number of papers contributed to by each author from that country or institution. However, that skews the results towards favouring papers with many authors (especially large collaborations with dozens of authors).

To maintain an equal footing across research papers so that each high-impact paper is equally important, we allocated a fractional research credit between the authors of each paper. Credit for each paper was distributed equally between the authors named on each individual paper.[156] For example, for a five-author paper, each author was attributed a 20% credit. In addition, the author's credit was partitioned further to each country or institution that the author was affiliated with on that paper. So, if one of those authors listed two separate institutions, each institution would receive half of that author's credit, which is 10% credit in this example. For each technology, we summed the individual country or institution credits from all the high-impact papers to determine the total number of high-impact papers for all countries or institutions. The following example shows what this looks like in practice.

Suppose a paper had the following authors with their respective institutional affiliations.



We did this for each paper and then summed the country or institution credits across all papers to determine its yearly credit.

What search terms did we use?

This update also incorporates improved search terms to accurately capture technological trends in the 21-year period (2003–2023) for each technology. Using those improved search terms, we downloaded 7.8 million publication records from the WoS. We improved the quality of this dataset, most notably by filtering out retracted or duplicate records and separating out and standardising country and institution names. Our final dataset contained 6.8 million unique publication records.

We have decided not to release the bespoke search terms so that countries, organisations and individuals are not able to manipulate future iterations of this project. Thank you to Australia's Defence Science and Technology Group for sharing material in 2022 that helped us start a library of search terms. We have since built our own expanded database search strategies, which we put a lot of effort into every year. Effort is also put into eliminating similar but unrelated terms. A concrete example comes from search terms used for *small satellites*. They're often referred to as microsatellites, but that same term also describes a section of DNA with repeating patterns that's important in cancer diagnosis. Best practice techniques for database queries were implemented to handle these edge cases.

How did we clean our datasets?

Allocating country and institution credit requires countries and institutions to be clearly identified so that variations of the same name can be counted together (for example, 'USA' and 'United States' should be considered the same country). The WoS address data is structured, in the sense that there's a general pattern in how the address is expressed. That pattern, however, is populated using human-entered data, is not strictly followed, so there's considerable variation in how authors reference their countries and especially their institutions.

In the case of country names, this process was relatively simple. The number of variations is relatively constrained because there are only a handful of cases in which genuine name variations exist (for example, 'the Czech Republic' versus 'Czechia'). We were therefore able to use and modify existing lists of country names and their variations to automate the cleaning of country names into a single standardised set.[157] For that set, we elected to use the Unicode Common Locale Data Repository (CLDR) standard.[158] This decision was made on the basis that CLDR better captures the customary names of countries as opposed to their official, although less commonly used, names (e.g. United Kingdom of Great Britain and Northern Ireland versus United Kingdom).

The standardisation of institution names was more intensive than standardising country names due to two main reasons:

1. the larger number of potential institutions and the much greater variation in how those institutions may be referred to
2. the need to consider aggregating institutions whose operations are very closely linked or managed or have in the 21-years, merged entirely

ASPI dealt with this through the creation of a custom institution dictionary that captures common spellings, aliases, name changes and organisational relationships of a long list of institutions. Since the initial release of the *Tech Tracker* in March 2023, this dictionary has been built up from its initial size of around 400 corrections to now more than 2,000. That increase was enabled by the development of a semi-automated cleaning pipeline that uses data from the Research Organisation Registry (ROR) to accelerate the rate at which corrections could be made. This was then supplemented with manual research using a variety of resources (including ASPI's *Chinese Defence Universities Tracker*[159]) to capture additional institutions not in the ROR database. An indicative example of the cleaning process is RTX Corporation. In 2020, Raytheon merged with United Technologies Corporation (UTC) to become Raytheon Technologies and inherited Pratt & Whitney, a major aerospace manufacturer that was a UTC subsidiary. In 2023, Raytheon Technologies was renamed to RTX Corporation. Therefore, all research done over the 21-year period by Pratt & Whitney, Raytheon and RTX is attributed to RTX Corporation. For each of these companies, we then need to consider possible name variations. For example, 'Pratt & Whitney' could also be 'Pratt and Whitney'. As an abbreviation, RTX might also be used by researchers from other similarly abbreviated institutions, in which case, more specific information about the location of the institution may need to be used.

Our dictionary, the result of considerable effort over a two-year period, currently contains more than 2,000 institutions from 86 countries, and we intend to expand it further as additional work is funded as a part of this project.

How do I read the historical time-series graphs and projection graphs?

The annual publication-rate graphs show the variation in the number of publications (top 10%) as a function of the publication year. This was done for either the top 5 institutions or the top 5 countries, with the rankings made by either their 2003–2023 performance (21-year ranking) or their 2019–2023 performance (recent ranking). The annual publication rate graphs (labelled (a) in the figures throughout this report) also show a centred five-year moving average. For example, the five-year moving average value in 2015 is the average of the values in 2013, 2014, 2015, 2016 and 2017. For ease of readability, partial averages were calculated and shown in the line graphs at the edges namely at publication years 2003, 2004, 2022, 2023. This is especially useful for smaller datasets in which significant fluctuations in performance are prominent.

The corresponding cumulative publications graphs—which we use to reflect longer term trends in ranking for a country's scientific and academic knowledge base—is a cumulative sum of the number of publications (top 10%) over the 21-year span. The cumulative publications graph is plotted with a five-year moving average and labelled (b) throughout this report. We interpret this quantity as a measure of the accumulated knowledge within a given country or institution: a horizontal trend line indicates no additional high-quality research, and that the knowledge base has more-or-less plateaued.

For both graphs (a) and (b), we made projections from their observed historical trend (2010-2023) up to the year 2030, to predict whether or when the lead country will be overtaken in its annual publication rate and its cumulative publications, respectively. The curves were fitted using a natural spline formula with one degree of freedom for the annual publication rate graphs and two degrees of freedom for the cumulative publication graphs. The projections were more representative of the expected behaviour at the edges compared to polynomial fitting,[160] especially for the cumulative publications' graphs. For our data, the intersection year (when present) was always extracted from the graphs for the US and China. Additionally, for technologies where a crossover in lead country has already occurred, the intersection years were read from the five-point average line, with the projection reserved for those technologies which have not yet seen a crossover take place. Those intersection years for all 64 technologies for the US and China plots are summarised in Appendix 3. The intersection years combined give estimated points in time of when the two countries' publication performance reached parity in the annual publication rate.

It should be noted, however, that breaking up our research dataset by institution rather than by country results in smaller subsets, and so the results are more sensitive to random variation. The cumulative publications graph is therefore more useful than the non-aggregated plot (annual publication rate) in analysing institutions, as the random variation is smoothed out when the results are aggregated over time.

What's the difference between the time-series graphs that use the number or percentage of papers?

Global research output has been growing exponentially since the beginning of scientific publishing in the late 17th century, and the current volume of scientific publications doubles roughly every 15 years.[161] Therefore, plotting the number of papers produced by a particular country in a particular field potentially emphasises this overall exponential growth rather than the relative country performance. To account for this, the performance of a country (or institution) can also be visualised on the website by their global share of high-impact research. This view makes it easier to compare country performance in earlier years, when global research output may have been smaller. However, caution must be exercised in earlier years (such as 2003-2007) in some emerging (or did not even exist yet) technologies where the global share is extracted from small numbers of publications.

To calculate the cumulative global share of publications, we divide the cumulative sum of high-impact publications for each individual country or institution by the cumulative sum of the global number of high-impact publications. Thus, the cumulative global share represents, at each point in time, the proportion of high-impact publications that the country or institution has accumulated compared to the world's high-impact publications since 2003.

What else is new in this *Critical Technology Tracker* update?

- **Talent Tracker:** In the March 2023 launch of the *Critical Technology Tracker*,[162] the research authors who were tracked were from research papers published between 2018 and 2022. In this release, we have shifted the publication time window to between 2019 and 2023 and updated our data to include any relevant additions to the ORCID database that have been made in the past year. Additionally, the *Talent Tracker* can now be viewed for all individual countries in the EU as well as for the EU as a whole.
- **Technology monopoly risk:** The *technology monopoly risk* for all 64 technologies has been updated with the 2019–2023 data, and to reflect improved search terms and institutions cleaning. See Appendix 1 for this updated summary.
- **Country groupings:** Additional country groups, such as the NATO alliance, have been added to the website.
- **Institution groupings:** Some institutions were partitioned into their different constituents, the intention being to best capture the institution that is doing the actual research, but we exercised some degree of judgement in our decision to aggregate or disaggregate. Our list of institutions was updated to better conform to the list used by *Nature* in its annual ranking of 18,000 of the world's research institutions.[163] Key changes that were made this year included the following:
  - The University of California system was separated into its constituent universities (UC Los Angeles, UC Davis, UC Berkeley etc).
  - The Indian Institutes of Technology were separated into the Indian Institute of Technology Delhi, the Indian Institute of Technology Roorkee etc.
  - In contrast, some research affiliations were aggregated, such as the National Institute of Allergy and Infectious Diseases, which was merged with the National Institute of Drug Abuse (and several more institutes) to form the National Institute of Health.

What is our methodology for the patent data?

This report includes some preliminary patent analysis on two technologies, *advanced integrated circuit design and fabrication* and *advanced aircraft engines* (based on the 2023 edition of the European Patent Office's worldwide patent statistical data set, PATSTAT,[164] and shared with us by IP Australia). This dataset contains data on patent applications made to various patenting authorities around the world. Each application is linked to two countries, an origin and publishing authority country. The origin country is based on the location of the applicant who filed the patent application and was therefore used to assign each patent to a particular country. The dataset also includes data relating each patent application to a patent family identified by their INPADOC patent family[165] id. What is commonly understood as an 'invention' is captured by these patent families, which may have many patent applications within each of them. These patent families are deemed 'active' if, there is at least one application in the patent family which was, as of 2023, either valid or pending review.

For each patent family, each distinct country present within the applications is given a credit of one. This potentially overstates the performance of countries with authors whose contribution to a patent family was relatively minor and a fractional allocation method (similar to what has been used to allocate research credit) could be considered in future work.

Patents are the natural progression of innovation in the science and technology landscape – often the middle step between research breakthroughs and commercialisation or more general technology actualisation. Like all indicators, there are advantages and drawbacks. For example, there can be incentives for firms to acquire patents even if they don't represent genuine innovations.[166] There can also be incentives for firms to *not* patent their most innovative breakthroughs, since that would both require disclosing trade secrets.[167] Others argue, however that patents promote knowledge diffusion and reduce technology duplication, increasing the efficiency with which innovative advances are made.[168] And while patents and innovation should not be conflated, patents nonetheless can track intangible dynamics of innovation, such as market dynamism, government regulation and human capital.[169]

Does the dataset include classified research?

This project uses publicly available data sources (including via paid subscription) and thus does not capture data which is not publicly available such as classified research conducted by governments. Similarly, research conducted by private companies that isn't publicly available isn't captured either.

Does the dataset include research not published in English?

98.42% of the 6.8 million research papers that form our research dataset are written in English. The next most common language is Chinese, which makes up 0.76% of research papers. Other languages that make up more than 0.1% of the dataset are German (0.14%), Spanish (0.13%) and Russian (0.10%). However, the subset of highly cited research papers, on which most of the analysis in this report is based, is much more heavily skewed towards English, which accounts for 99.97% of that subset, the rest being mostly accounted for by Chinese (0.02%). For better or worse, English is the current lingua franca of research.

It's been argued that Web of Science (along with its main competitor, Scopus) has a systematic bias against indexing research written in languages other than English.[170] Clarivate (the producer of the Web of Science) has taken steps in the past decade to better index non-English research, such as by integrating the SciELO index (which has strong coverage of Spanish and Portuguese language research), as well as the introduction of the Korean Citation Index, Russian Citation Index and Arabic Citation Index. It's probably still the case, however, that the coverage of English-language research is stronger than that of other languages. This is likely to favour the performance of countries with a high English literacy rate, where the barriers to publishing in a journal indexed by WoS and being cited by other researchers are lower than for researchers in countries with a low English literacy rate.

What is the ASPI Talent Tracker?

The ASPI Talent Tracker is a dataset created by ASPI that tracks the career trajectories of researchers working in each of the 64 critical technologies. It does this by using the ORCID database, which assigns a unique and persistent digital identifier (an ORCID iD) to researchers which can be used to link them to their professional activities (published papers, positions held and degrees/qualifications) and it means difficulties associated with actual names can be avoided (e.g. non-uniqueness, name changes, spelling variation, translatability, etc.). These ORCID iDs are often included by authors in their submissions to research journals, which is captured in the WoS database. Hence, by combining the ORCID iDs listed in the WoS database with the professional activities listed in the ORCID database, in addition to our long-term data cleaning efforts, we were able to create a dataset which visualises the flow of research talent (researchers who authored the top 25% or top 10% most cited papers). This means we can track the countries where they gained their undergraduate degree, their post-graduate qualification, and are most recently employed.

To ensure that only researchers that are still active in the field are visualised, only authors who published within the top 10% (or 25%) most cited papers between 2019 and 2023 (i.e. the last five years) are included in this dataset. You can read about the methodology in more detail in the 2023 report.[171] We also encourage you to explore this dataset on the website: techtracker.aspi.org.au. When using the website, and having selected a technology of interest (and optionally countries to focus on), this can be viewed by clicking on the 'flow of human talent' tab.

What is the Hirsch index (H-index)?

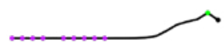
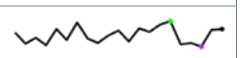
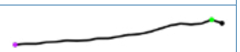
While not focused on in this report, on the *Tech Tracker* website, readers will see that we also use research published over the last five years to rank each country and institution by its H-index.[172] While the H-index is best known as a reflection of individual researchers' performance, it has several measurement properties that make it useful. You can read more about the H-index and how we used and examined some of that data in our 2023 report.[173]

How many research papers are included in your dataset?

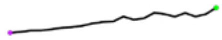
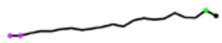
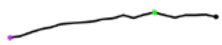
The level of research output is not uniform across each of the 64 technologies in the ASPI Critical Technology Tracker. In our 21-year dataset, *nanoscale materials and manufacturing* for example has 1,226,588 publications while *AI algorithms and hardware accelerators* has only 4,082 publications. Moreover, some critical technology areas have emerged recently while others have been established research areas for several decades. Our results from the 2000s should be understood with the context that for technologies which were emerging or did not even exist yet – and therefore have much smaller research paper datasets – the rankings are much more sensitive to minor variations. For example, twenty years ago, in a newly emerging technology area, a single high-impact research paper may be the difference between ranking 20th or 2nd.

In Table 1 below, we show the number of publications within our dataset for each technology, in addition to the number of publications within the top 10% of most cited papers. The table also shows the minimum and maximum papers from a single year for each technology within that top 10%. It also includes a sparkline ('hits-by-year') that shows the general trend of research volume in that technology, and in the overwhelming majority of cases that trend is clearly rising.

Table 1: Database search hits for each technology between 2003 and 2023 (purple and green points in sparkline represent years of minimum and maximum number of yearly hits respectively)

Technology	Database hits		Yearly database hits (top 10%)	
	All papers	Top 10%	Min - Max	Hits-by-year
Advanced information and communication technologies				
Advanced optical communication	48,179	5,147	104 - 467	
Advanced radiofrequency communication	50,916	5,229	23 - 805	
Advanced undersea wireless communication	10,038	1,094	6 - 131	
Distributed ledgers	29,019	3,025	1 - 742	
High performance computing	33,365	3,475	50 - 321	
Mesh and infrastructure independent networks	149,869	15,318	165 - 1,079	
Protective cyber security technologies	49,657	5,245	39 - 695	
Advanced materials and manufacturing				
Additive manufacturing	33,178	3,492	5 - 632	
Advanced composite materials	75,038	7,699	162 - 582	
Advanced explosives and energetic materials	15,639	1,626	33 - 129	
Advanced magnets and superconductors	26,295	2,764	116 - 151	
Advanced protection	20,654	2,192	29 - 239	
Coatings	27,241	2,780	54 - 243	
Continuous flow chemical synthesis	20,994	2,182	50 - 166	
Critical minerals extraction and processing	28,141	2,973	53 - 306	
High-specification machining processes	30,183	3,101	47 - 259	
Nanoscale materials and manufacturing	1,226,588	125,872	1,537 - 9,671	

Technology	Database hits		Yearly database hits (top 10%)	
	All papers	Top 10%	Min - Max	Hits-by-year
Novel metamaterials	33,583	3,540	11 - 505	
Smart materials	76,556	8,050	142 - 802	
Wide and ultrawide bandgap semiconductors	88,682	9,173	276 - 620	
AI technologies				
AI algorithms and hardware accelerators	4,082	434	1 - 90	
Advanced data analytics	60,296	6,214	55 - 614	
Advanced integrated circuit design and fabrication	25,714	2,702	65 - 182	
Adversarial AI	8,409	977	1 - 254	
Machine learning	953,699	103,150	845 - 18,778	
Natural language processing	91,462	9,777	100 - 1,085	
Biotechnology, gene technologies and vaccines				
Biological manufacturing	155,679	16,181	149 - 1,391	
Genetic engineering	151,710	15,931	469 - 1,468	
Genomic sequencing and analysis	344,574	36,994	831 - 4,010	
Novel antibiotics and antivirals	108,571	11,114	177 - 1,126	
Nuclear medicine and radiotherapy	191,839	19,975	412 - 1,706	
Synthetic biology	54,542	5,673	60 - 573	
Vaccines and medical countermeasures	95,593	9,876	77 - 1,749	
Defence, space, robotics and transportation				
Advanced aircraft engines	13,541	1,447	13 - 191	
Advanced robotics	130,186	13,473	139 - 1,582	
Autonomous systems operation technologies	66,028	6,964	79 - 845	
Drones, swarming and collaborative robots	22,553	2,306	13 - 296	
Hypersonic detection and tracking	3,633	398	5 - 42	
Small satellites	14,044	1,496	34 - 150	
Space launch systems	3,165	348	10 - 27	
Energy and environment				
Biofuels	112,795	11,677	34 - 998	
Directed energy technologies	27,502	2,846	31 - 296	

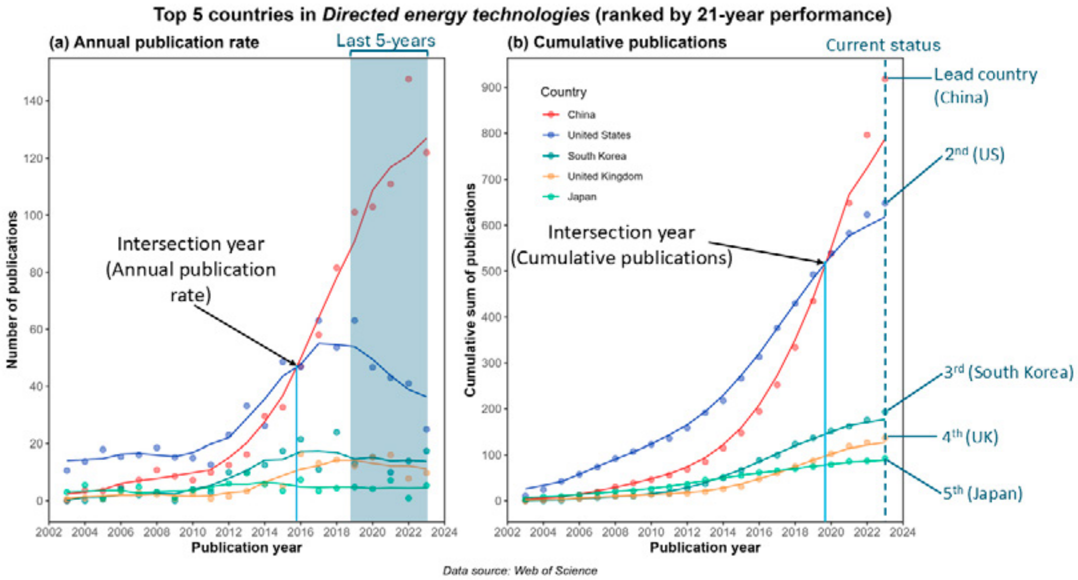
Technology	Database hits		Yearly database hits (top 10%)	
	All papers	Top 10%	Min - Max	Hits-by-year
Electric batteries	177,772	18,068	144 - 2,224	
Hydrogen and ammonia for power	132,500	13,450	122 - 1,222	
Nuclear energy	59,567	6,336	142 - 498	
Nuclear waste management and recycling	26,507	2,780	67 - 230	
Photovoltaics	296,077	30,732	295 - 2,774	
Supercapacitors	66,059	6,758	13 - 773	
Quantum				
Post-quantum cryptography	10,768	1,152	21 - 116	
Quantum communication	15,403	1,634	21 - 171	
Quantum computing	50,531	5,334	102 - 641	
Quantum sensors	47,231	4,892	115 - 397	
Sensing, timing and navigation				
Atomic clocks	15,110	1,617	39 - 120	
Gravitational-force sensors	9,669	1,026	25 - 76	
Inertial navigation systems	31,751	3,380	43 - 266	
Magnetic field sensors	11,389	1,200	27 - 101	
Multispectral and hyperspectral imaging sensors	50,996	5,380	80 - 612	
Photonic sensors	141,386	14,646	310 - 1,312	
Radar	915,887	94,187	2,797 - 5,986	
Satellite positioning and navigation	38,398	4,095	47 - 372	
Sonar and acoustic sensors	12,102	1,298	27 - 105	
Unique AUKUS technologies				
Air-independent propulsion	12,325	1,278	20 - 83	
Autonomous underwater vehicles	7,632	807	11 - 74	
Electronic warfare	11,921	1,251	22 - 104	

Note: The number of papers within the top 10% of most cited papers is not exactly 1/10th of the total number of papers in each technology due to papers with the same number of citations at the 0.9-quantile cut point.

Appendix 3: Summary of historical results (2003–2023)

In Figure 29, the graphs for each individual technology show the time evolution for the number of publications per year for different countries or over the past 21 years.

Figure 29: Explanatory graphs illustrating where the intersection years and the country ranking in the 21-year performance can be read. Note the years assessed over the last 5-year performance.



The intersection years shown in Figure 30 are *cross-over years when the lead country is overtaken by another country in its annual publication rate and cumulative publications*. The intersection years between 2005 and 2021 were read from the intersection of the 5-year average lines for the two countries. For intersection years beyond 2021, projections are made up to the year 2030 to determine potential future cross-over based on the 2010-2023 trends.

Table 2 compares the two lead countries over two time periods by aggregating the total publications across the past five years (recent) and the entire 21-year period (historical) in the 64 technologies.

Figure 30: The intersection years in annual publication rates and cumulative publications for the 64 technologies; their technology monopoly risk is also shown

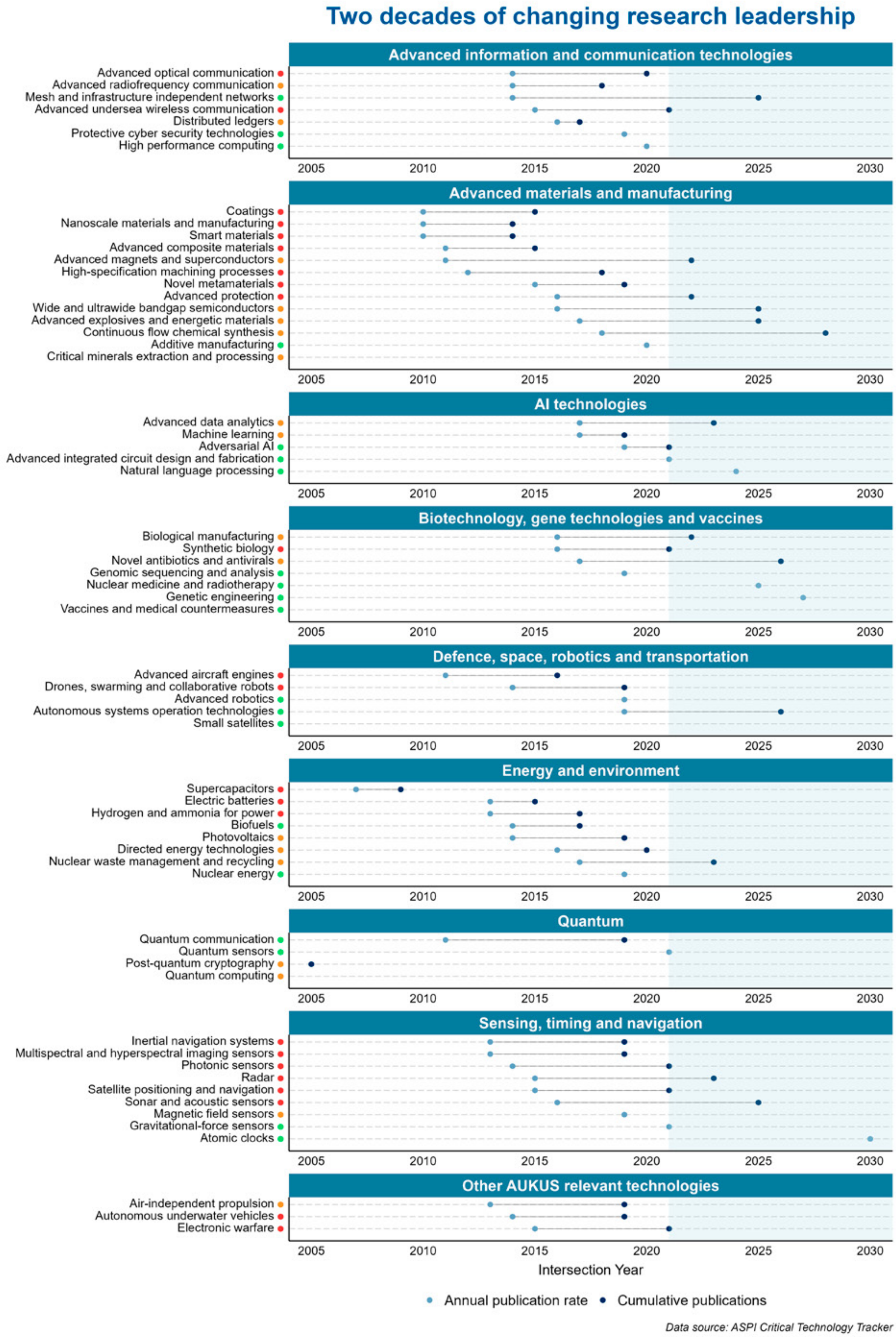


Table 2: Lead countries based on ranking in the past 5 years and 21 years and lead institution based on the 21-year ranking

Technology	Lead country: Past 5 years	Lead country: Past 21 years	Annual publication rate intersection year	Lead institution (21 years)
Advanced communication technologies				
Advanced radiofrequency communication	China	China	2014	Xidian University
Advanced undersea wireless communication	China	China	2015	Zhejiang University
Distributed ledgers	China	China	2016	Beijing University of Posts and Telecommunications
Mesh and infrastructure independent networks	China	USA	2014	University of Waterloo (Canada)
Advanced optical communication	China	China	2014	Chinese Academy of Sciences
Protective cybersecurity technologies	China	USA	2019	UNSW Sydney (Australia)
High-performance computing	China	USA	2020	Chinese Academy of Sciences
Advanced materials and manufacturing				
Coatings	China	China	2010	Chinese Academy of Sciences
Nanoscale materials and manufacturing	China	China	2010	Chinese Academy of Sciences
Advanced composite materials	China	China	2011	Chinese Academy of Sciences
Advanced explosives and energetic materials	China	USA	2017	Nanjing University of Science and Technology
High-specification machining processes	China	China	2012	Harbin Institute of Technology
Novel metamaterials	China	China	2015	Southeast University (China)
Smart materials	China	China	2010	Chinese Academy of Sciences
Wide and ultrawide bandgap semiconductors	China	USA	2016	Chinese Academy of Sciences
Advanced protection	China	China	2016	Dalian Maritime University (China)
Additive manufacturing	China	USA	2020	Nanyang Technological University
Continuous-flow chemical synthesis	China	USA	2018	Massachusetts Institute of Technology
Advanced magnets and superconductors	China	China	2011	Chinese Academy of Sciences
Critical minerals extraction & processing	China	China	n.a.	Chinese Academy of Sciences
AI technologies				
Advanced data analytics	China	China	2017	Chinese Academy of Sciences
Artificial intelligence algorithms and hardware accelerators	China	China	*	Tsinghua University
Adversarial AI	China	China	2019	Tsinghua University
Machine learning	China	China	2017	Chinese Academy of Sciences
Natural language processing	USA	USA	2024	Google
Advanced integrated circuit design and fabrication	China	USA	2021	Georgia Institute of Technology
Biotechnology, gene technologies and vaccines				
Synthetic biology	China	China	2016	Chinese Academy of Sciences
Biological manufacturing	China	China	2016	Chinese Academy of Sciences
Vaccines and medical countermeasures	USA	USA	n.a.	Harvard University
Novel antibiotics and antivirals	China	USA	2017	Chinese Academy of Sciences
Genome sequencing & analysis	China	USA	2019	Chinese Academy of Sciences
Genetic engineering	USA	USA	2027	Harvard University
Nuclear medicine and radiotherapy	USA	USA	2025	MD Anderson Cancer Center (US)
Defence, space, robotics and transportation				
Hypersonic detection and tracking	China	China	*	Northwestern Polytechnical University (China)
Advanced aircraft engines	China	China	2011	National University of Defense Technology (China)

Drones, swarming and collaborative robots	China	China	2014	Beihang University
Advanced robotics	China	USA	2019	Chinese Academy of Sciences
Autonomous systems operation technology	China	USA	2019	Massachusetts Institute of Technology
Space launch systems	China	USA	*	NASA
Small satellites	USA	USA	n.a.	California Institute of Technology
Energy and environment				
Electric batteries	China	China	2013	Chinese Academy of Sciences
Hydrogen and ammonia for power	China	China	2013	Chinese Academy of Sciences
Supercapacitors	China	China	2007	Chinese Academy of Sciences
Directed-energy technologies	China	China	2016	Korean Advanced Institute of Science and Technology (South Korea)
Nuclear waste management and recycling	China	China	2017	French Alternative Energies and Atomic Energy Commission (France)
Photovoltaics	China	China	2014	Chinese Academy of Sciences
Biofuels	China	China	2014	Chinese Academy of Sciences
Nuclear energy	China	USA	2019	Chinese Academy of Sciences
Quantum technologies				
Quantum computing	USA	USA	n.a.	Delft University of Technology (Netherlands)
Post-quantum cryptography	China	China	n.a.	University of Science and Technology of China
Quantum communication	China	China	2011	University of Science and Technology of China
Quantum sensors	China	USA	2021	Harvard University
Sensing, timing and navigation				
Inertial navigation systems	China	China	2013	Beihang University
Multispectral and hyperspectral imaging sensors	China	China	2013	Wuhan University
Photonic sensors	China	China	2014	Chinese Academy of Sciences
Sonar and acoustic sensors	China	USA	2016	University of California San Diego
Atomic clocks	USA	USA	2030	National Institute of Standards and Technology (US)
Radar	China	China	2015	Chinese Academy of Sciences
Satellite positioning and navigation	China	China	2015	Wuhan University
Gravitational-force sensors	China	USA	2021	Chinese Academy of Sciences
Magnetic-field sensors	China	USA	2019	Beihang University
Unique AUKUS-relevant technologies				
Autonomous underwater vehicles	China	China	2014	Harbin Engineering University
Electronic warfare	China	China	2015	National University of Defense Technology (China)
Air-independent propulsion	China	China	2013	Chinese Academy of Sciences

n.a. = technologies for which no change in the lead country was observed or is projected to happen by 2030.

* = cases in which the publications datasets were too small to determine an intersection year that shows a convincing changeover of lead countries.

Table 2 compares the two lead countries over two time periods by aggregating the total publications across the past five years (recent) and the entire 21-year period (historical) in the 64 technologies

Appendix 4: Selection of government agencies/laboratories in the *Critical Technology Tracker*

In addition to universities and companies, our institution dataset also includes more than 360 institutions, national research facilities or government research agencies/laboratories.[174] Here, we list those national or government facilities that rank especially highly (in the top 20) in one or more of ASPI's 64 critical technologies for research conducted either between 2003 and 2007 or between 2019 and 2023.

Australia

Commonwealth Scientific and Industrial Research Organisation (CSIRO)

Austria

Austrian Academy of Sciences

Canada

National Research Council Canada

China

Chinese Academy of Agricultural Sciences
China Academy of Engineering Physics
Chinese Academy of Sciences
China Aerodynamics Research & Development Center (CARDC)
China Earthquake Administration

Egypt

Egyptian Atomic Energy Authority
National Research Centre
Nuclear Materials Authority

France

French Alternative Energies and Atomic Energy Commission (CEA)
French National Centre for Scientific Research
National Institute for Research in Digital Science and Technology (Inria)
National Office for Aerospace Studies and Research (ONERA)

Germany

Fraunhofer Society
German National Metrology Institute
Helmholtz Association of German Research Centres
Leibniz Association

India

Council of Scientific & Industrial Research
Defence Research and Development Organisation

Italy

National Institute of Nuclear Physics

Japan

Japan Aerospace Exploration Agency
Japan Atomic Energy Agency
National Institute for Material Science
National Institute of Advanced Industrial Science and Technology (AIST)

Japan Agency for Marine-Earth Science and Technology (JAMSTEC)
Japan Science and Technology Agency

Netherlands

Energy Research Centre of the Netherlands

Norway

Norwegian Defence Research Establishment

Russia

Russian Academy of Sciences

Singapore

Agency for Science, Technology & Research (A*STAR)

South Korea

Korea Atomic Energy Research Institute

Spain

Spanish National Research Council
Centre for Energy, Environmental and Technological Research (CIEMAT)

United Kingdom

National Physical Laboratory

United States

Agricultural Research Service
Argonne National Laboratory
Centers for Disease Control and Prevention
Idaho National Laboratory
Lawrence Livermore National Laboratory
Los Alamos National Laboratory
National Aeronautics and Space Administration
National Institutes of Health
National Institute of Standards and Technology
National Oceanic and Atmospheric Administration
National Renewable Energy Laboratory
Oak Ridge National Laboratory
Pacific Northwest National Laboratory
Sandia National Laboratories
United States Air Force Research Laboratory
United States Army Combat Capabilities Development Command
United States Geological Survey
United States Naval Research Laboratory

Notes

1 *Critical Technology Tracker*, ASPI, Canberra, online.
2 Jamie Gaida, Jennifer Wong Leung, Stephan Robin, Danielle Cave, *ASPI's Critical Technology Tracker: the global race for future power*, ASPI, Canberra, 1 March 2023, online.
3 21-year dataset with improved search terms and institution cleaning, see Methodology for more details.
4 In the early years, such as 2003–2007, some of the 64 technologies have not yet emerged and the credits assigned to top countries or institutions are too low to be statistically significant. Where this is the case we have avoided pulling key insights from the rankings of countries and institutions in these technologies.
5 Bec Crew, 'Nature Index 2024 Research Leaders: Chinese institutions dominate the top spots', *Nature*, 18 June 2024, online.
6 Elsa B Kania, 'Opinion: Why doesn't the US have its own Huawei?', *Politico*, 25 February 2020, online.
7 See, for example, Zachary Arnold, 'China has become a scientific superpower', *The Economist*, 12 June 2024, online; 'China', *Nature*, 9 August 2023, online; 'China's science and technology vision' and 'China's breakout research capabilities in defence, security and intelligence technologies' in Gaida et al., *ASPI's Critical Technology Tracker: The global race for future power*, 14–20; Tarun Chhabra et al., 'Global China: Technology', Brookings Institution, April 2020, online; Jason Douglas and Clarence Leong. "The U.S. Has Been Spending Billions to Revive Manufacturing. But China Is in Another League", *The Wall Street Journal*, August 3, 2024, online.
8 Eva Harris, 'Building scientific capacity in developing countries', *EMBO Reports*, 1 January 2004, 5, 7–11, online.
9 These technologies were selected through a review process in 2022–23 that combined our own research with elements from the Australian Government's 2022 list of critical technologies, and lists compiled by other governments. An archived version of the Australian Government's list is available: Department of Industry, Science and Resources, 'List of critical technologies in the national interest', Australian Government, 28 November 2022, online. In May 2023, the Australian Government revised their list: Department of Industry, Science and Resources, 'List of critical technologies in the national interest', Australian Government, 19 May 2023, online. A US list is available from National Science and Technology Council, 'Critical and emerging technologies list update', US Government, February 2022, online. On our selection of AUKUS Pillar 2 technologies, see Alexandra Caples et al., 'AUKUS: three partners, two pillars, one problem', *The Strategist*, 6 June 2023, online.
10 Felix Poege et al., 'Science quality and the value of inventions', *Science Advances*, 11 December 2019, 5(12):eaay7323, online; Cherng Ding, et al., 'Exploring paper characteristics that facilitate the knowledge flow from science to technology', *Journal of Informetrics*, February 2017, 11(1):244–256, online; Gaida et al., *ASPI's Critical Technology Tracker: The global race for future power*, 9.
11 Jamie Gaida, Jennifer Wong Leung, Stephan Robin, Danielle Cave, *ASPI's Critical Technology Tracker: The global race for future power.*
12 See more details in the full methodology in Appendix 2.
13 'List of technologies', *Critical Technology Tracker*, online.
14 *Critical Technology Tracker*, online.
15 See Jamie Gaida, Jennifer Wong-Leung, Stephan Robin, Danielle Cave, *ASPI's Critical Technology Tracker: the global race for future power.*
16 Jamie Gaida, Jennifer Wong-Leung, Stephan Robin, Danielle Cave, *ASPI's Critical Technology Tracker: the global race for future power*, 44.
17 Noting that China's investment in manufacturing and the support it provides factories is reportedly far larger than any other country, see Jason Douglas and Clarence Leong, 'The U.S. Has Been Spending Billions to Revive Manufacturing. But China Is in Another League', *The Wall Street Journal*, August 3, 2024, online.
18 'Lithium-ion battery manufacturing capacity, 2022–2030', International Energy Agency, 22 May 2023, online.
19 For quantum computing, see Sam Howell, *The quest for qubits: assessing US–China competition in quantum computing*, Center for a New American Security, May 2024, online. For vaccines, see Alexandra Stevenson, 'These vaccines have been embraced by the world. Why not in China?', *New York Times*, 18 February 2022, online.
20 See Appendix 1 for full details of how we have calculated the technology monopoly risk metric and for relevant results.
21 Please note that some of the technologies we track were just beginning to emerge during the period 2003–2007. We avoid ranking technologies for which the dataset is too small for rankings past the leading country to be statistically significant. For example, in this period, India also ranked 4th in additive manufacturing, with a high-impact research credit of 2 papers.
22 These are Sathyabama Institute of Science and Technology in *biofuels,* Nirma University in *distributed ledgers,* the Vellore Institute of Technology and Anna University (Chennai) in *mesh and infrastructure independent networks*¸ and the Homi Bhabha National Institute in *nuclear waste management and recycling.* In this update of the *Critical Technology Tracker*, the Indian Institute of Technology and the National Institute of Technology (which were strong Indian performers in our previous report) were disaggregated into their individual institutes to conform to their separate listing in the *Nature* index (see full methodology in Appendix 2).
23 For more on Horizon Europe see Horizon Europe, European Commission, online.
24 For more see Marie Skłodowska-Curie Actions, European Commission, online.
25 The Helmholtz Association of German Research Centres and National Research Council (Italy) for example, are two of the EU's most prominent research institutions covered by the *Critical Technology Tracker.* In our 21-year dataset, these institutions have collectively published over 25,000 research papers supported by these programs.
26 This is based on technologies where the number of high-impact publications of Iran is statistically significant for the ranking.

27 Note that we focused our search terms on compact energy generation and potential relevance for AUKUS Pillar 2's 'undersea capabilities'.

28 Department of Defense, 'AUKUS: The trilateral security partnership between Australia, UK and US', US Government, no date, online; 'Fact Sheet: Implementation of the Australia – United Kingdom – United States Partnership (AUKUS)', Australian Government, no date, online.

29 Our lead indicator for risk associated with high concentrations of S&T expertise in a single country.

30 Jamie Gaida, Jennifer Wong-Leung, Stephan Robin, Danielle Cave, *ASPI's Critical Technology Tracker: the global race for future power.*

31 Nokia (US) is the AT&T Bell Labs as Nokia acquired Bell Labs in 2016. All publications under AT.T. Bell Labs and Lucent Technologies listed under the US affiliations are aggregated as Nokia (US).

32 'CAS institutes', Chinese Academy of Sciences (CAS), 2024, online. Note that we counted the universities under CAS management as separate institutions.

33 See Appendix 4 for a more comprehensive (though still necessarily selective) list of government research entities that we see in our data.

34 See Jamie Gaida, Jennifer Wong-Leung, Stephan Robin, Danielle Cave, *ASPI's Critical Technology Tracker: the global race for future power.*

35 Jamie Gaida, Jennifer Wong-Leung, Stephan Robin, Danielle Cave, *ASPI's Critical Technology Tracker: the global race for future power*, 9

36 Web of Science, Clarivate, online.

37 Junwen Zhu, Weishu Liu, 'A tale of two databases: the use of Web of Science and Scopus in academic papers', *Scientometrics*, 2020, 123:321–335, online; Kai Li, Jason Rollins and Erjia Yan, 'Web of Science use in published research and review papers 1997–2017: a selective, dynamic, cross-domain, content-based analysis', *Scientometrics*, 2018, 115:1–20, online.

38 Research Organization Registry, online.

39 The same methodology as used in the first report. See Jamie Gaida, Jennifer Wong-Leung, Stephan Robin, Danielle Cave, *ASPI's Critical Technology Tracker: the global race for future power*, 11.

40 'Radar', Critical Technology Tracker, online.

41 'Where is a patent valid and how long does it last?', European Patent Office, 2024, online.

42 'Taiwan's dominance of the chip industry makes it more important', *The Economist*, 6 March 2023, online.

43 For more background on patent data the detailed methodology in Appendix 2.

44 'How to build science capacity: eight leaders propose ways to boost research in their countries in the next decade, *Nature*, 1 October 2012, 490:331–334, online.

45 Learn more about the *Talent Tracker* in the detailed methodology in Appendix 2 and the results can be found on our website techtracker.aspi.org.au.

46 'Mesh and infrastructure independent networks', *Critical Technology Tracker*, ASPI, online.

47 See Jamie Gaida, Jennifer Wong-Leung, Stephan Robin, Danielle Cave, *ASPI's Critical Technology Tracker: the global race for future power.*

48 'National University of Defense Technology', *China Defence Universities Tracker*, ASPI, Canberra, online.

49 'Nanjing University of Aeronautics and Astronautics, University of Defense Technology', *China Defence Universities Tracker*, online.

50 The 'Seven Sons of National Defence' (国防七子) are a group of leading universities with deep roots in the military and defence industry. They're subordinate to the Ministry of Industry and Information Technology which oversees China's defence industry through its subordinate agency, the State Administration of Science, Technology and Industry for National Defense (SASTIND). For more see Alex Joske, 'The China Defence Universities Tracker: Exploring the military and security links of China's universities', ASPI, Canberra, 25 November 2019, online.

51 Omar Memon, 'Top 5: The world's largest jet engine manufacturers', *Simple Flying*, 14 September 2023, online.

52 Chinese companies produce 90% of commercial drones used in the US and 77% of those flown by hobbyists, according to US House of Representatives committee data. David J Lynch, 'Chinese subsidies for drones, chips put US at risk, House panel says', *Washington Post*, 26 June 2024, online.

53 John Bannister Goodenough, Michael Stanley Whittingham and Akira Yoshino were jointly awarded the 2019 Nobel Prize in Chemistry for the development of lithium-ion batteries. 'The Nobel Prize in Chemistry 2019', media release, Royal Swedish Academy of Sciences, 9 October 2019, online.

54 Zeyi Yang, 'How did China come to dominate the world of electric cars?', *MIT Technology Review*, 21 February 2023, online.

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Acronyms and abbreviations

AI	artificial intelligence
BUPT	Beijing University of Posts and Telecommunications
CAS	Chinese Academy of Sciences
CATL	Contemporary Amperex Technology Co. Limited
CETC	China Electronics Technology Group Corporation
CLDR	common locale data repository
DARPA	Defense Advanced Research Projects Agency (US)
DUV	deep ultraviolet
EPFL	École Polytechnique Fédérale de Lausanne (Federal Institute of Technology of Lausanne)
EU	European Union
EUV	extreme ultraviolet
EV	electric vehicle
IMEC	Interuniversity Microelectronics Centre
LLM	large language model
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NLP	natural language processing
nm	nanometre
NUAA	Nanjing University of Aeronautics and Astronautics
NUDT	National University of Defense Technology (China)
ORCID	Open Researcher and Contributor ID
PLA	People's Liberation Army
PV	photovoltaics
R&D	research and development
ROR	Research Organization Registry
S&T	science and technology
SMIC	Semiconductor Manufacturing International Corporation
TSMC	Taiwan Semiconductor Manufacturing Company Limited
UESTC	University of Electronic Science and Technology of China
USTC	University of Science and Technology of China
UTC	United Technologies Corporation
WoS	Web of Science

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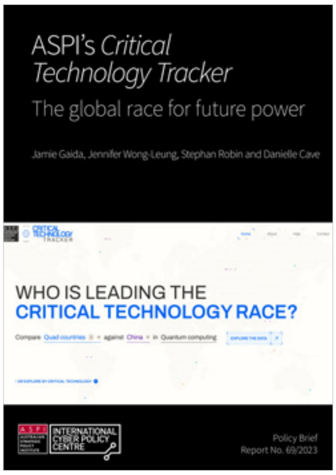

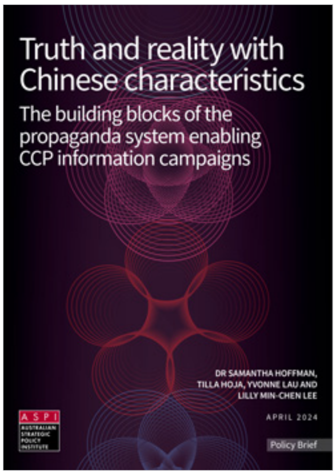

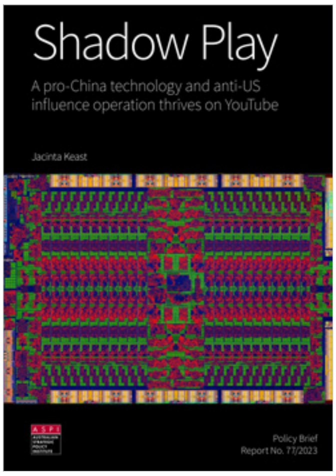

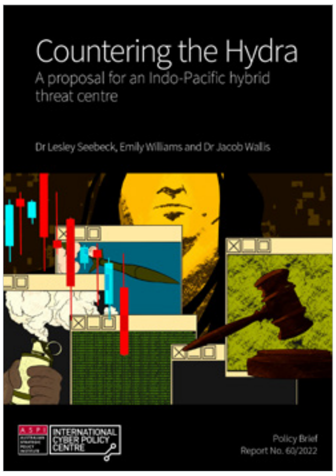

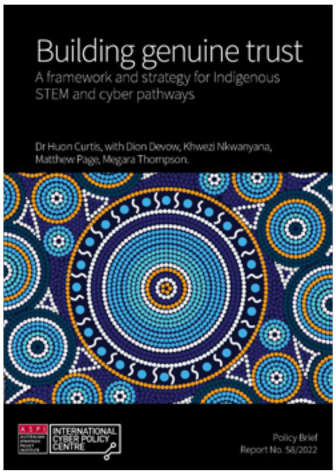

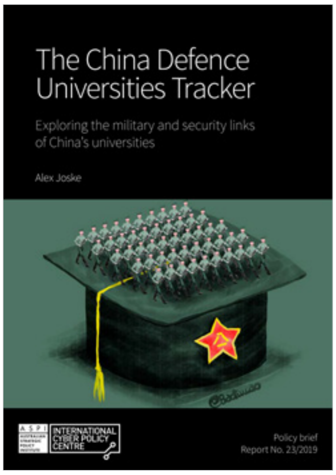

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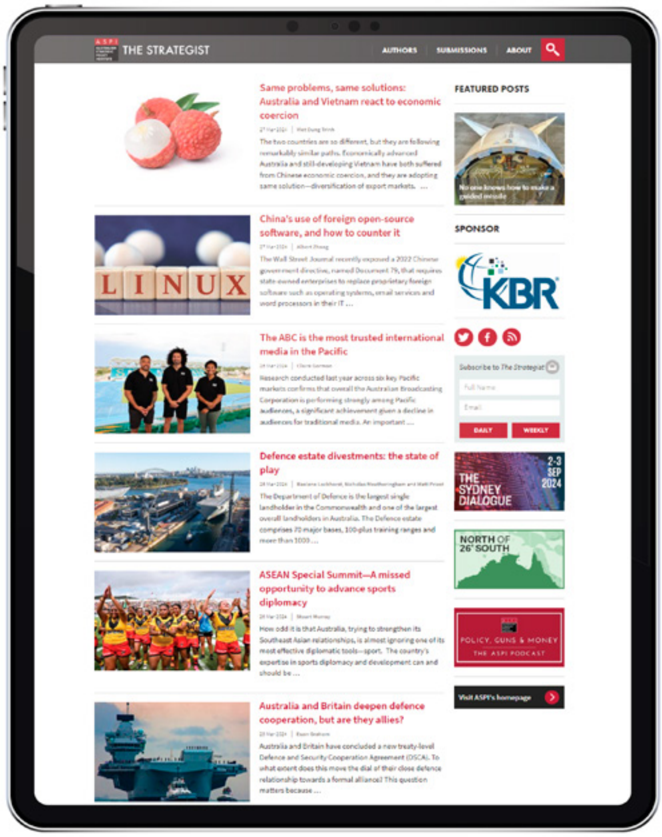

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