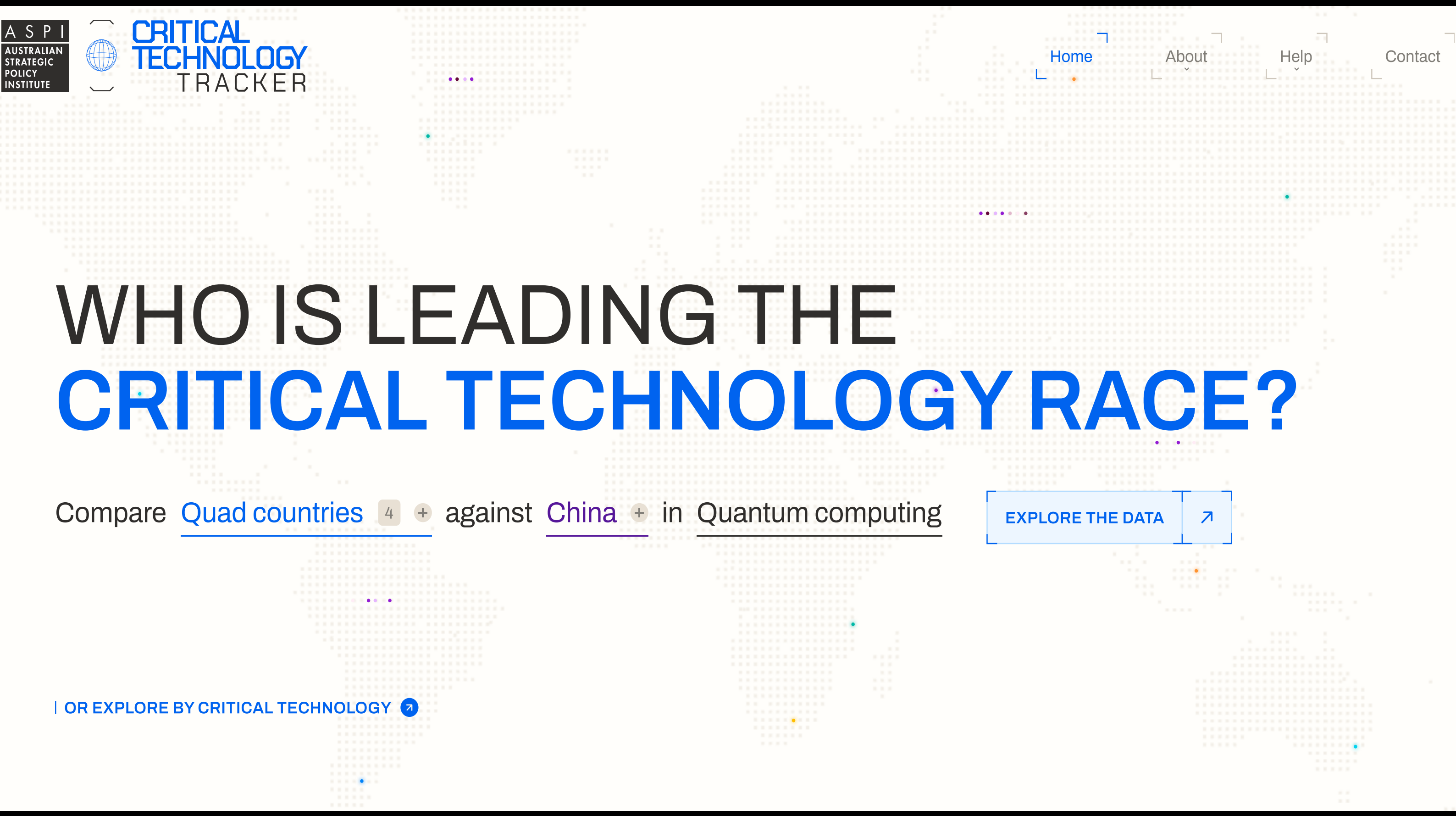
ASPI's *Critical Technology Tracker*

The global race for future power

Jamie Gaida, Jennifer Wong-Leung, Stephan Robin and Danielle Cave



ASPI AUSTRALIAN STRATEGIC POLICY INSTITUTE
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About the authors

Dr Jamie Gaida is a senior analyst, project manager and data scientist with ASPI's International Cyber Policy Centre.

Dr Jennifer Wong-Leung is a data scientist with ASPI's International Cyber Policy Centre.

Stephan Robin is a researcher with ASPI's International Cyber Policy Centre.

Danielle Cave is Director – Executive, Strategy & Research at ASPI.

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ASPI

Tel Canberra: +61 2 6270 5100
Tel Washington DC: +1 202 414 7353
Email enquiries@aspi.org.au
www.aspi.org.au
www.aspistrategist.org.au
facebook.com/ASPI.org
@ASPI_ICPC

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Contents

What's the problem?

Western democracies are losing the global technological competition, including the race for scientific and research breakthroughs, and the ability to retain global talent—crucial ingredients that underpin the development and control of the world's most important technologies, including those that don't yet exist.

Our research reveals that China has built the foundations to position itself as the world's leading science and technology superpower, by establishing a sometimes stunning lead in high-impact research across the majority of critical and emerging technology domains. China's global lead extends to 37 out of 44 technologies that ASPI is now tracking, covering a range of crucial technology fields spanning defence, space, robotics, energy, the environment, biotechnology, artificial intelligence (AI), advanced materials and key quantum technology areas.[1] The *Critical Technology Tracker* shows that, for some technologies, all of the world's top 10 leading research institutions are based in China and are collectively generating nine times more high-impact research papers than the second-ranked country (most often the US). Notably, the Chinese Academy of Sciences ranks highly (and often first or second) across many of the 44 technologies included in the *Critical Technology Tracker*. We also see China's efforts being bolstered through talent and knowledge import: one-fifth of its high-impact papers are being authored by researchers with postgraduate training in a Five-Eyes country.[2] China's lead is the product of deliberate design and long-term policy planning, as repeatedly outlined by Xi Jinping and his predecessors.[3]

A key area in which China excels is defence- and space-related technologies. China's strides in nuclear-capable hypersonic missiles reportedly took US intelligence by surprise in August 2021.[4] Had a tool such as ASPI's *Critical Technology Tracker* been collecting and analysing this data two years ago, Beijing's strong interest and leading research performance in this area would have been more easily identified, and such technological advances would have been less surprising. That's because, according to our data analysis, over the past five years, China generated 48.49% of the world's high-impact research papers into advanced aircraft engines, including hypersonics, and it hosts seven of the world's top 10 research institutions in this topic area.

The US comes second in the majority of the 44 technologies examined in the *Critical Technology Tracker*. The US currently leads in areas such as high performance computing, quantum computing and vaccines. Our dataset reveals that there's a large gap between China and the US, as the leading two countries, and everyone else. The data then indicates a small, second-tier group of countries led by India and the UK: other countries that regularly appear in this group—in many technological fields—include South Korea, Germany, Australia, Italy, and less often, Japan.

This project—including some of its more surprising findings—further highlights the gap in our understanding of the critical technology ecosystem, including its current trajectory. It's important that we seek to fill this gap so we don't face a future in which one or two countries dominate new and emerging industries (something that recently occurred in 5G technologies) and so countries have ongoing access to trusted and secure critical technology supply chains.

China's overall research lead, and its dominant concentration of expertise across a range of strategic sectors, has short and long term implications for democratic nations. In the long term, China's leading research position means that it has set itself up to excel not just in current technological development in almost all sectors, but in future technologies that don't yet exist. Unchecked, this could shift not just technological development and control but global power and influence to an authoritarian state where the development, testing and application of emerging, critical and military technologies isn't open and transparent and where it can't be scrutinised by independent civil society and media.

In the more immediate term, that lead—coupled with successful strategies for translating research breakthroughs to commercial systems and products that are fed into an efficient manufacturing base—could allow China to gain a stranglehold on the global supply of certain critical technologies. Such risks are exacerbated because of the willingness of the Chinese Communist Party (CCP) to use coercive techniques[5] outside of the global rules-based order to punish governments and businesses, including withholding the supply of critical technologies.[6]

What's the solution?

These findings should be a wake-up call for democratic nations, who must rapidly pursue a strategic critical technology step-up. Governments around the world should work both collaboratively and individually to catch up to China and, more broadly, they must pay greater attention to the world's centre of technological innovation and strategic competition: the Indo-Pacific. While China is in front, it's important for democracies to take stock of the power of their potential aggregate lead and the collective strengths of regions and groupings (for example the EU, the Quad and AUKUS, to name just a few examples). But such aggregate leads will only be fully realised through far deeper collaboration between partners and allies, greater investment in areas including R&D, talent and commercialisation, and more focused intelligence strategies. And, finally, governments must make more space for new, bigger and more creative policy ideas - the step-up in performance required demands no less.

Partners and allies need to step up and seriously consider things such as sovereign wealth funds at 0.5%–0.7% of gross national income providing venture capital, research and scale-up funding, with a sizable portion reserved for high-risk, high-reward 'moonshots' (big ideas). Governments should plan for:

- technology visas, 'friend-shoring' and R&D grants between allies
- a revitalisation of the university sector through specialised scholarships for students and technologists working at the forefront of critical technology research
- restructuring taxation systems to divert private capital towards venture capital and scale-up efforts for promising new technologies
- new public–private partnerships and centres of excellence to help to foster greater commercialisation opportunities.

Intelligence communities have a pivotal role to play in both informing decision-makers and building capability. One recommendation we make is that Five-Eyes countries, along with Japan, build an intelligence analytical centre focused on China and technology (starting with open-source intelligence).

We outline 23 policy recommendations for partners and allies to act on collaboratively and individually. They span across the four themes of investment and talent; global partnerships; intelligence; and moonshots. While China is in front, it's important for democracies to take stock of their combined and complementary strengths. When added up, they have the aggregate lead in many technology areas.

What is ASPI's *Critical Technology Tracker*?

ASPI's new *Critical Technology Tracker* website (https://techtracker.aspi.org.au/) provides the public with a rich new dataset that allows users to track 44 technologies foundational for our economies, societies, national security, energy production, health and climate security. Both the website and this report provide decision-makers with a new evidence base to make more informed policy and investment decisions. A list of these 44 technologies, including definitions, can be found here.

This effort goes further than previous attempts to benchmark research output across nations by focusing on individual institutions and technologies, identified as being critical and emerging, rather than focusing on total research output. Technology definitions can be found on the website.[7] This report is broken into key sections:

Methodology: We provide an explanation of why tracking high-impact research is a useful measure of where countries, universities and companies are excelling. We explain our methodology in detail and provide 'deep dives' into our dataset to explore three major fields: AI, quantum technologies and advanced materials.

Analysis: This research focuses on a key performance measure of scientific and technological capability—high-impact research—and reveals where countries, universities and companies around the world have a competitive advantage in this measure across the 44 technologies. The talent tracker also examines other metrics to reveal the flow of global talent in these technologies and to highlight brain gains and brain drains for each country. Our analysis of the dataset also helps policymakers understand where the concentration of research expertise is most extreme and could threaten future access to key technologies.

Visual Snapshot: Readers looking for a visual summary of the top-5 ranked countries (see example below) in each of the 44 technology areas can jump to Appendixes 1.1 and 1.2. Appendix 4 is a table of flags and the countries that they represent.

Technology	Top 5 countries				
Vaccines and medical countermeasures	 28.31%	 12.57%	 6.18%	 6.06%	 5.14%
Advanced aircraft engines (incl. hypersonics)	 48.49%	 11.69%	 6.96%	 3.93%	 3.60%

Given China's strengths in so many of these technologies, this report unpacks elements of China's lead, including by examining China's breakout research capabilities in defence, security and intelligence technologies, along with the long-term policy and planning efforts that underpinned this outcome.

Recommendations: The report provides 23 policy recommendations geared towards closing the critical technologies research gap.

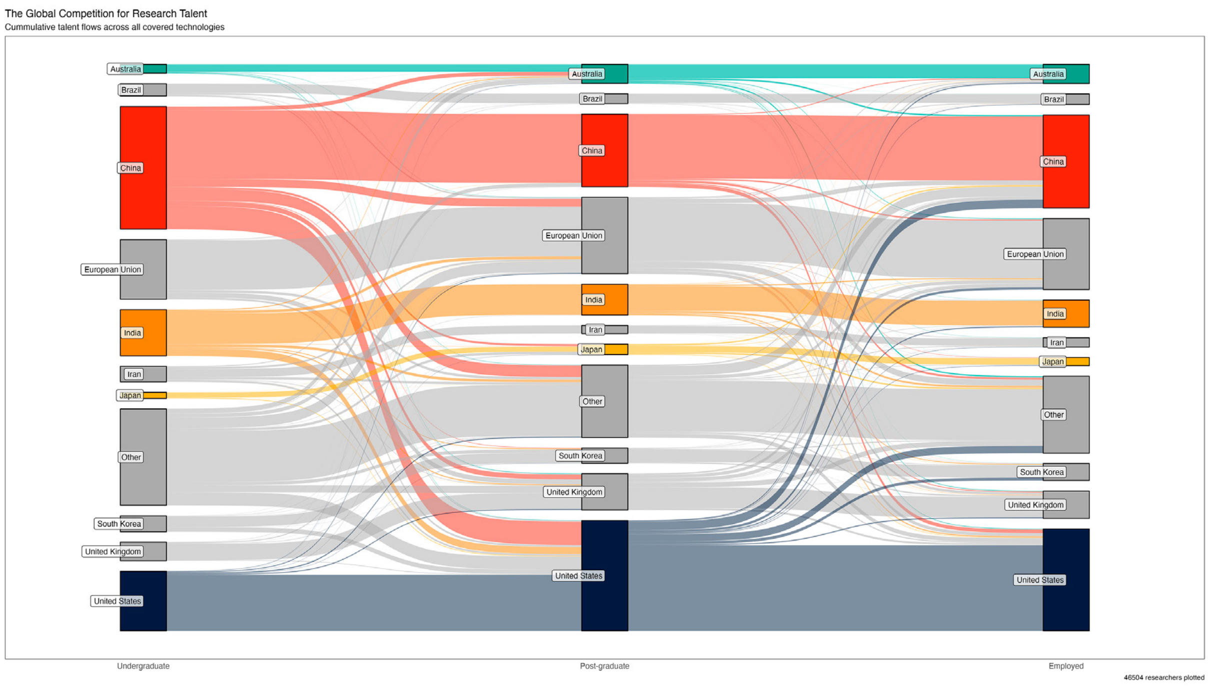
ASPI's *Critical Technology Tracker* website contains an enormous amount of original data and analysis, and we encourage readers to visit the site and explore the data as they engage with this report. ASPI aims for the tracker to be used by policymakers, businesses, researchers and media. We'll continue to build and improve this program of work over the coming years, including by adding more technologies and possibly more features.

Executive summary

Critical technologies already underpin the global economy and our society. From the energy-efficient microprocessors in smartphones to the security that enables online banking and shopping, these technologies are ubiquitous and essential. They're unlocking green energy production and supporting medical breakthroughs. They're also the basis for military capability on the battlefield, are underpinning new hybrid warfare techniques and can give intelligence agencies a major edge over adversaries.

Just a few years ago, a nation could focus its research, resource extraction and manufacturing energies toward its strengths with the assurance that international supply chains would provide the balance of required goods. That world has gone, swept away by Covid-19, geopolitics and changes in global supply chains. Countries have also shown a willingness to withhold supplies of critical materials as a weapon of economic coercion, and an energy crisis is gripping much of the world as a result of the Russian invasion of Ukraine.

This report, and the *Critical Technology Tracker* website, fill a global gap by identifying which countries, universities and businesses are leading the effort to progress scientific and research innovation, including breakthroughs, in critical technologies. Database queries identified the relevant set of papers for each technology (2.2 million in total; see our method in brief on page 10 and in detail in Appendix 2).[8] The top 10% most highly cited research publications from the past five years on each of the 44 technologies were analysed. In addition, our work collecting and analysing data on the flow of researchers between countries at various career stages—undergraduate, postgraduate and employment—identifies brain drains and brain gains in each technology area. See below talent flow graphic that illustrates the global competition for research talent across these 44 technologies.



China is further ahead in more areas than has been realised. It's the leading country in 37 of the 44 technologies evaluated, often producing more than five times as much high-impact research as its closest competitor. This means that only seven of the 44 analysed technologies are currently led by a democratic country, and that country in all instances is the US.

The US maintains its strengths in the design and development of advanced semiconductor devices and leads in the research fields of *high performance computing* and *advanced integrated circuit design and fabrication*. It's also in front in the crucial areas of *quantum computing* and *vaccines (and medical countermeasures)*. This is consistent with analysis showing that the US holds the most Covid-19 vaccine patents and sits at the centre of this global collaboration network.[9] Medical countermeasures provide protection (and post-exposure management) for military and civilian people against chemical, biological, radiological and nuclear material by providing rapid field-based diagnostics and therapeutics (such as antiviral medications) in addition to vaccines.[10]

The race to be the next most important technological powerhouse is a close one between the UK and India, both of which claim a place in the top five countries in 29 of the 44 technologies. South Korea and Germany follow closely behind, appearing in the top five countries in 20 and 17 technologies, respectively. Australia is in the top five for nine technologies, followed closely by Italy (seven technologies), Iran (six), Japan (four) and Canada (four). Russia, Singapore, Saudi Arabia, France, Malaysia and the Netherlands are in the top five for one or two technologies. A number of other countries, including Spain and Turkey, regularly make the top 10 countries but aren't in the top five.

As well as tracking which countries are in front, the *Critical Technology Tracker* highlights which organisations—universities, companies and labs—are leading in which technologies. For example, the Netherlands' Delft University of Technology has supremacy in a number of quantum technologies. A range of organisations shine through, including the University of California system, the Chinese Academy of Sciences, the Indian Institute of Technology, Nanyang Technological University (NTU Singapore), the University of Science and Technology China and a variety of national labs in the US (such as the Lawrence Livermore National Laboratory). The Chinese Academy of Sciences is a particularly high performer, ranking in the top 5 in 27 of the 44 technologies tracked by the Critical Technology Tracker. Comprising of 116 institutes (which gives it a unique advantage over other organisations) it 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. In addition, US technology companies are well represented in some areas, including in the AI category: Google (1st in *natural language processing*), Microsoft (6th by H-index and 10th by 'highly cited' in *natural language processing*), Facebook (14th by H-index in *natural language processing*), Hewlett Packard Enterprise (14th by H-index in *high performance computing*) and IBM (Switzerland and US arms both tying at the 11th place with other institutions by H-index in *AI algorithms and hardware accelerators)*.

There's a human dimension to technology development that should also be factored into assessments of technological capability. Innovations are ultimately the result of researchers, scientists and designers with a lifetime of training and experience that led to their breakthroughs. Understanding where those researchers started their professional journeys, where they received the training that equipped them to be leaders in their fields, and finally where they are now as they make their discoveries, paints a picture of how well countries are competing in their ability to attract and retain skilled researchers from the global pool of talent.

Who are the individuals publishing the high-impact research that's propelled China to an impressive lead? Where did they study and train? In *advanced aircraft engines (including hypersonics)*, in which China is publishing more than four times as much high-impact research as the US (2nd place), there are two key insights. First, the majority (68.6%) of high-impact authors trained at Chinese universities and now work in Chinese research institutions. Second, China is also attracting talent to the workplace from democratic countries: 21.6% of high-impact authors completed their postgraduate training in a Five-Eyes country (US = 9.8%, UK = 7.8%, Canada = 3.9%, Australia = none, New Zealand = none), 2% trained in the EU, and 2% trained in Japan. Although not quantified in this work, this is very likely to be a combination of Chinese nationals who went abroad for training and brought their newly acquired expertise back to China, and foreign nationals moving to China to work at a research institution or company.

World-leading research institutes typically also provide training for the next generation of innovators through high-quality undergraduates, masters and PhDs, and employment opportunities in which junior researchers are mentored by experts. As China claims seven of the world's top 10 research institutions for *advanced aircraft engines (including hypersonics),* its training system is largely decoupled, as there's a sufficient critical mass of domestic expertise to train the next generation of top scientists. However, a steady supply of new ideas and techniques is also provided by individuals trained overseas who are attracted to work in Chinese institutions.

A crucial question to ask is whether expertise in high-impact research translates into (sticking with the same example) the manufacture of world-leading jet engines. What of reports of reliability problems experienced with Chinese-manufactured jet engines?[11] The skill set required for leading-edge engine research differs from the expertise, tacit knowledge and human capital needed to manufacture jet engines to extreme reliability requirements.[12] This is an important caveat that readers should keep in mind, and it's one we point out in multiple places throughout the report. As one external reviewer put it, 'If you're good at origami but don't yet excel at making decent paper, are you really good at origami?' Naturally, manufacturing capability lags research breakthroughs. However, in the example of jet-engine manufacturing, China appears to be making strides[13] and has recognised the 'choke-point' of being entirely reliant on US and Swedish companies for the precision-grade stainless steel required for bearings in high performance aircraft engines.[14] China's excellent research performance in this area most likely reflects the prioritisation and investment by the CCP to overcome the reliability, and choke-point, hurdles of previous years.[15]

But whether the focus is jet engines or advanced robotics, actualising research performance, no matter how impressive, into major technological gains can be a difficult and complicated step that requires other inputs (in addition to high quality research). However, what ASPI's new *Critical Technology Tracker* gives us - beyond datasets showing research performance - are unique insights into strategy, intent and potential future capabilities. It also provides valuable insights into the spread, and concentrations of, global expertise across a range of critical areas.

There are many ways in which countries (governments, businesses and civil society) can use the new datasets available in the *Critical Technology Tracker.* It can be used to support strategic planning, enable more targeted investment, or facilitate the establishment of new global partnerships (to name just a few possibilities). For example, Australia has one of the world's biggest lithium reserves and has all the critical minerals for making lithium batteries.[16] As an established leader in *photovoltaics* technology,[17] Australia has the potential to guarantee its energy security by focusing on *electric batteries, critical minerals extraction* and *processing* and *photovoltaics technologies* while locally capitalising on its onshore critical-minerals resources. As the world's second largest producer of aluminium, Australia can reduce its greenhouse emissions by using both hydrogen and electricity generated from renewable sources in its aluminium production.[18] Strategic funding in these interconnected critical technology could reduce the current tech monopoly risks revealed by the *Critical Technology Tracker* and support new tech industries with job creation.

These findings should be a wake-up call for democratic nations. It has become imperative, now more than ever, that political leaders, policymakers, businesses and civil society use empirical open-source data to inform decision-making across different technological areas so that, in the years and decades to come, they can reap the benefits of new policies and investments they must make now. Urgent policy changes, increased investment and global collaboration are required from many countries to close the enormous and widening gap. The costs of catching up will be significant, but the costs of inaction could be far greater (Table 1).

Table 1: Lead country and technology monopoly risk.

Technology	Lead country	Technology monopoly risk
Advanced materials and manufacturing		
1. Nanoscale materials and manufacturing	China	high
2. Coatings	China	high
3. Smart materials	China	medium
4. Advanced composite materials	China	medium
5. Novel metamaterials	China	medium
6. High-specification machining processes	China	medium
7. Advanced explosives and energetic materials	China	medium
8. Critical minerals extraction and processing	China	low
9. Advanced magnets and superconductors	China	low
10. Advanced protection	China	low
11. Continuous flow chemical synthesis	China	low
12. Additive manufacturing (incl. 3D printing)	China	low
Artificial intelligence, computing and communications		
13. Advanced radiofrequency communications (incl. 5G and 6G)	China	high
14. Advanced optical communications	China	medium
15. Artificial intelligence (AI) algorithms and hardware accelerators	China	medium
16. Distributed ledgers	China	medium
17. Advanced data analytics	China	medium
18. Machine learning (incl. neural networks and deep learning)	China	low
19. Protective cybersecurity technologies	China	low
20. High performance computing	USA	low
21. Advanced integrated circuit design and fabrication	USA	low
22. Natural language processing (incl. speech and text recognition and analysis)	USA	low
Energy and environment		
23. Hydrogen and ammonia for power	China	high
24. Supercapacitors	China	high
25. Electric batteries	China	high
26. Photovoltaics	China	medium
27. Nuclear waste management and recycling	China	medium
28. Directed energy technologies	China	medium
29. Biofuels	China	low
30. Nuclear energy	China	low
Quantum		
31. Quantum computing	USA	medium
32. Post-quantum cryptography	China	low
33. Quantum communications (incl. quantum key distribution)	China	low
34. Quantum sensors	China	low
Biotechnology, gene technology and vaccines		
35. Synthetic biology	China	high
36. Biological manufacturing	China	medium
37. Vaccines and medical countermeasures	USA	medium
Sensing, timing and navigation		
38. Photonic sensors	China	high
Defence, space, robotics and transportation		
39. Advanced aircraft engines (incl. hypersonics)	China	medium
40. Drones, swarming and collaborative robots	China	medium
41. Small satellites	USA	low
42. Autonomous systems operation technology	China	low
43. Advanced robotics	China	low
44. Space launch systems	USA	low

Note: A visual summary of the top 5 countries for each technology area can be found in Appendix 1.1

Why research is vital for scientific and technological advancements

We selected one of many potential methodological approaches (citations of scientific publications) because research publications are a major contributor to technological, scientific and commercial strength.[19] The effect is most pronounced for high-quality papers (that is, the most highly cited).[20] For example, 80% of research papers in the top 0.01% of high-quality research (measured by three-year citation counts) are referenced in patents.[21] This drops to 60% for the top 0.1% and 40% for the top 1%. This known connection between the most cited research and patented technical breakthroughs has been used as a proxy to measure relative institutional and national standing (see 'Methodology' section).

In stark contrast, those research reports in the bottom 50% are almost never cited in patents. The rate of growth in citations from patents is related to the number of citations from scientific papers and journal quality rank.[22] Patents that reference high-quality science are referenced by subsequent patents twice as often,[23] and patents referenced by other patents have greater value.[24] Patents that directly reference research papers deliver 26% more commercial value[25] than otherwise comparable patents that are disconnected from research. Science-intensive patents are high-risk, high-reward ventures.[26] That is, a higher proportion of them are of low value, but the successful ones have much greater payoff, which increases the average value. Cited research publication data is thus a reliable measure of scientific advances and potential technological capability.

ASPI's *Critical Technology Tracker* and this report seek to assess the potential future capability of nations within each critical technology and to highlight long-term strategic trends including areas of focus for each country. We recognise that this snapshot in time (2018–2022) across each technology won't reveal all commercialisations or show us rates of technology diffusion (how populations adopt innovations and new technologies) or necessarily reflect levels of investments that countries are making in certain technologies or the technologies that will end up in manufacturing. As we use public data, we can't estimate the volume or quality of classified research conducted by governments and industry.

Nor does this project seek to provide a stand-alone metric to measure what might make a country an influential 'science and technology power'. While there's no such agreed definition, a range of factors could be taken into account beyond high performance in science and technology research; they could include policy implementation, entrepreneurship, commercialisation rates, regulatory frameworks, critical infrastructure, thought leadership, technology diplomacy (for example, influence in multilateral forums and in building coalitions of countries) and so on.

But as we raised earlier in this report, what this project does provide - in addition to new datasets on research performance - are unique insights into strategy and intent. It also provides valuable insights into the spread, and concentrations of, global expertise across a range of critical areas. Finally, it shows us what potential future technology leadership could look like (given scientific and technological innovation and breakthroughs are so often underpinned by research, and, most of all, by high-impact research).

Several other data sources are used to examine the technical capability of nations, and we evaluated many of them for potential inclusion in this project.[27] Patent registration is the key mechanism for protecting the commercial value of new inventions. Analysis of patent citations and patent ownership according to country is a rich source of insight. However, determining the country of origin and ownership is a complicated process. Similarly, analysis of venture capital funding could provide valuable insight into the intensity of technical innovation. Unfortunately, obtaining consistent and trustworthy data is extremely challenging, especially at the international level. Thematic analysis of national research priority and strategy documents provides insight into ambition and focus but not necessarily into output and capability. Of course, were it available, a detailed and consistent dataset of current research funding from around the globe would be an ideal leading indicator of research effort, but it's also worth noting that spending doesn't always equate to impact and innovation.

Consideration of all of those limitations steered us towards using citations of research publications. International publishing conventions are relatively consistent, scientific publishing is a key output of research innovation, and citation metrics provide a consistent (if not universally agreed) method for identifying high-impact research at scale. Publication (that is, bibliographic) databases are especially rich and provide researcher details, including workplace address (that is, affiliation) and a unique researcher identifier known as an ORCID iD (Open Researcher and Contributor ID).[28] The latter item allows dataset linkage and enables career-progression tracking. This reveals the countries (and organisations) that are gaining and retaining the world's top technological talent.

We expect that the results will be a surprise to some and are confident that they'll trigger public debate. Our hope is that the debate will centre upon whether we accept the risks highlighted and, if not, what policy and investment efforts, including collective action by states, are required. It would be a missed opportunity for the debate to get stuck on the relative merit of one analytical approach over another, rather than the overall trajectory and trends. We hope that the findings of this project will help build momentum towards solutions and a pathway forward. We also hope that debates will spur further attempts to measure relative capability by refining this method or developing new approaches.

Methodology in brief

A full and detailed methodology can be found in Appendix 2 which starts on page 57. Below, we explain why we focused on quality of research over quantity of research to rank countries and organisations (largely universities, businesses and national labs).

What do we mean by 'quality metrics'?

Distinguishing innovative and high-impact research papers from low-quality papers is critical when estimating the current and future technical capability of nations. Not all the millions of research papers published each year are high quality.

What's a citation?

When a scientific paper references another paper, that's known as a citation. The number of times a paper is cited reflects the impact of the paper. As time goes by, there are more opportunities for a paper to be cited, so only papers of a similar age should be compared using citation counts (as was done in this report).

Country-level quality metrics

Throughout this research project, we present three country-level quality metrics:

1) proportion of papers in the top 10% most highly cited research reports

2) the H-index

3) the number of research institutions a country has in the world's top 10–20 highest performing institutions.

The top 10% of the most highly cited papers were analysed to generate insights into which countries are publishing the greatest share of high-quality, innovative and high-impact research.[29] Credit for each publication was divided among authors[30] and their affiliations and not assigned only to the first author (for example, if there were two authors, they would each be assigned half the allocation). Fractional allocation of credit is a better prediction of individuals who go on to win Nobel Prizes or fellowship of prestigious societies.[31] Fractional allocation of credit was used for all metrics.[32]

The *H-index* (Hirsch index) is an established performance metric used for analysing the impact of scholarly output and is calculated from citation numbers of an individual's set of publications.[33] It's a combined measure of quantity and impact and performs better than other single-number summaries of research quality.[34] Calculating the H-index with five years worth of data (as we do in this research) eliminates a key criticism, which is that highly cited papers from decades ago boost the H-index but don't reflect current research excellence.[35] Another criticism of the H-index is that publication volumes vary by field of research, and this can unfairly advantage those in a field with high publication rates.[36] The H-index quality metric used here compares countries within the same technology area. This approach reduces but doesn't eliminate that problem.[37] Neither individual papers with extreme citation numbers nor a large number of papers with low citation counts inflate the H-index used here. We calculate the five-year H-index at the institution[38] and country levels.[39]

We include both the top 10% and the H-index as neither is perfect and both add a unique insight. In technologies in which 1st and 2nd place flip depending on which quality metric is used, the race really is too close to call. However, more often, the lead is large and unambiguous, and both metrics are consistent regarding who is leading.

The number of institutions that a country has in the world's top 10 institutions is used to illustrate research concentration and dominance. This list is based on the number of papers that the institutions have in the top 10% of highly cited papers.[40]

To build ASPI's new *Critical Technology Tracker* website, we collected and analysed research papers published between 2018 and 2022 in 44 technology areas. The technologies selected were informed by our own internal discussions and those with government officials and other stakeholders who highlighted areas of particular interest. Where possible we covered all technologies within a category (e.g. energy and environment), and aim to provide analysis of additional technologies later this year. For each technology, a custom search query was developed for the Web of Science database. This identified 2.2 million research papers that we subsequently used for analysis (see Appendix 2). Web of Science (Core Collection) is heavily used by researchers who study scientific trends and it has well understood performance characteristics.[41]

Bespoke search queries were developed for each technology area (see Appendix 2). We took particular effort to achieve the right balance between sensitivity and specificity, and ensure correct grouping of Boolean operators. Each query was carefully designed to capture the bulk of relevant papers while simultaneously excluding irrelevant papers. Each individual search generated a different size dataset (range 871 to 526,738: see Appendix 3 for exact numbers). The size differences reflect global publishing activity for each technology and the balance between sensitivity and specificity.[42] The bibliographic records used were restricted to journal articles, proceedings[43] and data papers.[44] This restricted the dataset to exclude bibliographic records that didn't reflect recent research advances, such as book reviews, retracted publications and letters submitted to academic journals.

We have decided not to release the search terms—of which there are hundreds of carefully crafted terms and search strings—so that countries, organisations and individuals are not able to manipulate future iterations of this project. Thank you also to Australia's Defence Science and Technology Group for sharing material that helped inform the development and build of our own database search strategies, which we put many months of effort into.

Results weren't filtered by language, but the overwhelming majority of reports (98.7%) were written in English.[45] This means that research papers published in domestic journals in, say, Japan, China, South Korea, France or Indonesia, outside of the world's major journals, aren't captured in this data collection, and that's of course a limitation. However, incentivised by the parameters within performance reviews, and ambitions to deliver impact, be promoted and receive grant income, researchers and scientists prioritise their most important research for high-profile journals. In fact, Chinese researchers are paid large personal bonuses for publishing in top-tier journals.[46] Databases such as the Web of Science aim to index the high-profile journals.

We chose the Web of Science database as it provides the necessary fields for our analysis, including the affiliation addresses of authors (to determine country and institution), authors' ORCID iD numbers (to determine career histories) and citation counts (to identify high-quality publications). The ability to download data for offline analysis was also a determining factor.

We focused on the top 10% of most highly cited papers as our first quality measure for countries and institutions (universities, labs and companies). The number of papers is sometimes used as a measure of research impact, but our focus was on comparing, and differentiating, quantity and quality metrics in our datasets based on categories (and subcategories) of different technologies. It's critically important to distinguish between quality and quantity. Other studies have also focused on assessing quality or 'high impact' or 'top tier' research as a measure to compare different countries' performance.[47] A 2020 MacroPolo study, for example, used papers submitted to a 2019 AI conference on deep learning to create a dataset of researchers and to track, for example, their country affiliations, institutions and career paths.[48] The top 1% of most highly cited papers has also been used in some studies as a quality metric for countries,[49] but the size of our dataset (2018–2022) was sometimes too small in individual technology areas to limit our study to the top 1%. For instance, for the talent tracker, with a smaller dataset, there's a risk of over-reading the data by following the talent flow of only a handful of researchers.

As an alternative and a second quality metric, the H-index[50] was also calculated for countries and institutions. Self-citations, in which an individual cites their own work, are a known limitation of citation analysis,[51] including the H-index,[52] but it should be acknowledged that self-citations can be legitimate.[53] Parochial citation practices, in which researchers are more likely to cite papers from their own country, are also detected in the literature.[54] This practice will boost citation rates for countries publishing a large volume of papers.

We wanted to place these quality metrics within a geographical context, so we summarised, using large-scale data analytics, the institution and the host country for each author from their affiliation address for each paper. Note that during the publishing process authors are required to provide the name and address of their research institutes. When a researcher changes jobs, their affiliation address changes. This is reflected in papers published after they move but isn't retrospectively applied to earlier papers. For researchers affiliated with more than one institution, we divided their per-author allocation of credit further between each institution. For example, an author on a five-author paper who has two affiliations will divide their 20% weighting —10% for each institution.

We also used big-data analytics to count how many of the world's leading research institutions are based in the lead country (by the number of papers in the top 10% of highly cited papers) combined with how far ahead the 1st country is relative to the 2nd country (see Appendix 1.1 for further details) and below we explain how we developed a technology monopoly risk traffic light system which focuses on concentrations of technological expertise in a single country.

'Technology monopoly risk' metric: highlighting concentrations of technological expertise

low medium high

The technology monopoly risk traffic light seeks to highlight *concentrations of technological expertise in a single country*. It incorporates two factors: how far ahead the leading country is relative to the next closest competitor, and how many of the world's top 10 research institutions are located in the leading country. Naturally, these are related, as leading institutions are required to produce high-impact research. This metric, based on top 10% *research output*, is intended as a leading indicator for potential future dominance in *technology capability* (such as military and intelligence capability).

The default position is low. To move up a level, *BOTH criteria must be met*.

- High risk = **8+/10** top institutions in no. 1 country *and* at least **3x research lead**
- Medium risk = **5+/10** top institutions in no. 1 country *and* at least **2x research lead**
- Low risk = medium criteria not met.

Example: If a country has a 3.5 times research lead but 'only' four of the top 10 institutions, it will rate low, as it fails to meet *both criteria* at the medium level.

Top 5 country rankings: The two metrics along with the traffic light are given in the right hand column of *top 5 country rankings* tables throughout the report and in Appendix 1.1 in full.

We also tracked the global flow of human talent by identifying the countries in which authors obtained their undergraduate and postgraduate degrees. This information was obtained from the ORCID database.[55] The current (or most recent) country of employment was sourced from the Web of Science dataset. Career histories were extracted for the authors of papers in the top 25% most highly cited papers in each technology area. Tracking flows between countries at three points in time slices the data into numerous possibilities (n^3, where n is the number of countries). This means that a larger dataset, with more authors, was required in order to generate reliable insights. In addition, it wasn't possible to build career histories for all authors. Not all authors have an ORCID iD (although registration is free) or remember to provide their ORCID iD when publishing. Additionally, not all ORCID records contain enough information to create a career history.[56] Thus, the talent-flow charts in this report are effectively tracking a sample of authors from high-impact papers.[57] At a minimum, we needed a country listed for a bachelor degree (or equivalent) and a country listed for a postgraduate degree (masters, PhD, or equivalent).

This analysis revealed the brain gains and brain drains for each country (see the talent flow graphic on page 4—global competition for research talent—as one example). The 27 member states of the EU, are grouped together in the talent tracker visualisations to represent the cumulative strength of the bloc. Although undoubtedly there is talent competition within the EU, the shared geostrategic interests of the EU member states, and the relative ease with which talent can move within the Schengen Area, led to the decision to aggregate their contributions in the global flow of talent. The unaggregated visualisations can be found on the ASPI *Critical Technology Tracker*.

In all talent tracker visualisations, the four members of the Quadrilateral Security Dialogue (the US, Australia, India and Japan), also known as the Quad, were plotted, as was China. The other countries tracked in this plot are the top five performers (in terms of global proportion of talent) not already visualised, and the remaining countries are grouped together under 'other'.

China's science and technology vision

China's commanding lead in high-impact research in almost every critical technology we tracked may be surprising for many. However, the CCP has been signalling, for decades now, the importance it places on technological advancement, talent, research and 'emerging strategic industries',[58] and those priorities are regularly and publicly outlined in its visions and plans.[59]

The desire of the People's Republic of China (PRC) to become a technological superpower stems all the way back to the exploitation of China's weaknesses by foreign powers possessing superior military technology during the 'century of humiliation'.[60] Already evident in the early planning days of the PRC under Mao Zedong, this ambition was enshrined in CCP ideology in the concept of 'self-reliance' (则力更生), forming the basis for what's now known as China's 'techno-nationalism'.[61] More recently, in the past two decades, Xi Jinping has added additional emphasis to these concepts, and has made investment and resourcing science and technology, as well as R&D, a core pillar of China's development and innovation strategies.

In his speech at the 18th National Congress of the CCP in 2012, Xi's predecessor, Hu Jintao, outlined that 'the contribution of scientific and technological progress to economic growth should increase considerably and China should become an innovative country', because 'scientific and technological innovation provides strategic support for raising the productive forces and boosting the overall national strength, and we must give it top priority in overall national development.'[62]

Later, in 2017, the report of the 19th Congress reiterated that:

> [W]e should aim for the frontiers of science and technology, strengthen basic research, and make major breakthroughs in pioneering basic research and groundbreaking and original innovations. We will strengthen basic research in applied sciences, launch major national science and technology projects, and prioritize innovation in key generic technologies, cutting-edge frontier technologies, modern engineering technologies, and disruptive technologies. These efforts will provide powerful support for building China's strength in science and technology, product quality, aerospace, cyberspace, and transportation; and for building a digital China and a smart society.[63]

In the years following the 19th Congress, scientific and technological innovation came to constitute the central propelling force for economic and social development for China's leadership, but also the 'main battlefield of the international strategic game', as Xi Jinping himself put it in a speech in May 2021.[64] To win the strategic game, these speeches materialised into practical initiatives to boost China's indigenous innovation and technological self-reliance, such as 'Made in China 2025' (中国制造 2025) and the 'dual circulation' economic strategy. The first was launched in 2015 and aimed to build China into a manufacturing superpower with a world-leading technology and industrial system.[65] Both have the explicit aim of boosting China's domestic demand while reducing its industries' reliance on foreign companies.[66] While Made in China 2025 took a lower profile in the past few years following international criticism,[67] such efforts are still visible in the latest initiative launched in December 2022—the Strategic Plan for Expanding Domestic Demand 2022–2035[68]—which has been interpreted as a revamping of Made in China 2025.[69]

The elevation of science and technology to the very top of the list of national priorities for the PRC's leadership is reflected in the number of officials with technical expertise who were elected to the apex of the CCP's ranks during the 20th, and latest, National People's Congress in 2022. The CCP Central Committee went from including fewer than 20 technocrats in 2017 to include almost 40 in 2022, while the Politburo went from two to a total of eight (out of 24 members).[70] At the 2022 congress, Xi again noted not only the fundamental importance of research, but also the power of talent, and went on to list the areas in which China has made great steps forward:

> We have grown stronger in basic research and original innovation, made breakthroughs in some core technologies in key fields, and boosted emerging strategic industries. We have witnessed major successes on multiple fronts, including manned spaceflight, lunar and Martian exploration, deep sea and deep earth probes, supercomputers, satellite navigation, quantum information, nuclear power technology, airliner manufacturing, and biomedicine. China has joined the ranks of the world's innovators.[71]

We should expect the CCP to continue to follow through on its strategic vision for science and technology. Developing a global lead in high-impact research will help support future technological and scientific advances and breakthroughs that will underpin everything from developments in green energy and biotechnology to new military and intelligence capabilities. Benchmarking the current state of the competition in these separate areas—including where the CCP is focusing its research and talent-development efforts—is of key importance in understanding how China intends to leverage technological innovation to reshape the global technology and geopolitical landscape and position itself at the apex.

China’s breakout research capabilities in defence, security and intelligence technologies

China’s dominance in high-impact research in technologies related to defence, space and security is clear from the *Critical Technology Tracker* dataset. Below is a visual snapshot showing the top five countries ranked by their proportion (%) of high-impact research output in six technologies in those fields.[72]

Four scenario-based examples are provided below, drawing upon applications at the intersection of multiple technologies in which China has the most striking lead: advanced aircraft engines (including hypersonics); future intelligence capability; AI; and drones. It’s worth noting that, beyond the six technologies listed, many more of the 44 technologies covered in the *Critical Technology Tracker* have obvious and less obvious military and security applications, ranging from *advanced materials* (such as *coatings*) to *advanced data analytics*.

As a reminder: the ‘technology monopoly risk’ column on the right-hand side of this visual snapshot contains three metrics:

1. The top number is the no. 1 country’s share of the world’s top 10 high-performing institutions.
2. The next figure is the no. 1 country’s lead in publications over its closest competitor (ratio of respective share of the top 10% publications).
3. A traffic light rating in which:

High risk = **8+/10** top institutions in no. 1 country *and* at least **3x research lead**

Medium risk = **5+/10** top institutions in no. 1 country *and* at least **2x research lead**

Low risk = medium criteria not met.

A table of flags and the countries that they represent is in Appendix 4.

Defence, space, robotics and transportation

Table 2: Top 5 country rankings: Defence, space, robotics and transportation.

Technology	Top 5 countries					Technology monopoly risk
Advanced aircraft engines (incl. hypersonics)	China 48.49%	United States 11.69%	India 6.96%	United Kingdom 3.93%	Iran 3.60%	7/10 4.15 **medium**
Drones, swarming and collaborative robots	China 36.07%	United States 10.30%	Italy 6.13%	India 5.15%	United Kingdom 4.53%	5/10 3.50 **medium**
Small satellites	United States 24.49%	China 17.32%	Italy 7.82%	Germany 4.36%	United Kingdom 4.11%	5/10 1.41 **low**
Autonomous systems operation technology	China 26.20%	United States 21.01%	United Kingdom 5.28%	Germany 5.11%	South Korea 3.55%	3/10 1.25 **low**
Advanced robotics	China 27.89%	United States 24.64%	United Kingdom 5.49%	Italy 4.81%	South Korea 3.79%	4/10 1.13 **low**
Space launch systems	United States 19.67%	China 18.24%	Germany 9.81%	Canada 8.18%	South Korea 6.53%	1/10 1.08 **low**

Defence breakthroughs: advanced aircraft engines (including hypersonics) / surveillance balloons

The world was shocked in October 2021 when it was revealed in media reporting that the PRC had tested a nuclear-capable hypersonic glide vehicle.[73] However, that shouldn't have been a huge surprise, given that China has a 48% share of the world's most high-impact research on '*advanced aircraft engines (incl. hypersonics)*'. The key challenges of achieving speeds above Mach 5 can be addressed by prioritising advances in low-friction surfaces to reduce and dissipate heat produced by air friction and the development of novel materials able to handle high temperatures and high forces on control surfaces.[74] Our surprise should have been even less had we also known that China is the global leader in other technological fields relevant to advancing hypersonic missiles, including *novel metamaterials* (46% of world's top 10% high impact research output, 2.7 times that of the second placing country, the US), *coatings* (58%, 7.96 times the US), and *high-specification machining processes* (36%, 2.62 times India). Building a world-dominating lead in these distinct but interrelated research fields may have been a happy coincidence for the PRC, but it was more likely to have resulted from a well-laid strategy, spanning decades, that helped support the development of hypersonic vehicle test-flights.[75]

Recent events that have put a spotlight on China's surveillance balloon activity highlight integration between research programs with defence applications in the Chinese Academy of Sciences [76] (high-altitude balloon research, military intelligence, surveillance and reconnaissance, and hypersonic weapons testing), which can be seen through the *Critical Technology Tracker*.

The Chinese Academy of Sciences is a stand-out performer in the *Critical Technology Tracker* datasets. It leads in six of the eight *energy and environment* technologies (no. 1 globally for *electric batteries*, *hydrogen and ammonia for power*, *nuclear energy*, *nuclear waste management and recycling*, *photovoltaics*, *supercapacitors*, no. 3 for *biofuels*; and no. 8 for *directed energy technologies*) and several critical defence and space technologies (no. 1 for *photonic sensors* and *quantum sensors*, and no. 2 for *advanced robotics* and *small satellites*). The Chinese Academy of Sciences is also no. 1 for *advanced data analytics* and no. 2 for *machine learning* in the *artificial intelligence, computing and communications* category.

Although balloons are conceptually low tech, their ability to (at least sometimes) slip through detection systems and carry heavy payloads is extremely valuable. The *Financial Times* reported that Chinese state television showed footage of high-altitude balloons carrying hypersonic glide vehicles in 2018, but that the video is no longer available.[77] Video matching the description can be found on Twitter[78] and Toutiao.[79] Comments below the video state these were scale models of hypersonic glide vehicles used for testing, and suggest the wing design matches the 'I-plane hypersonic concept' from the Chinese Academy of Sciences.[80] The 2018 research paper describing this design has been cited by, so far, 19 subsequent research papers.[81] Thus, it's likely that high-altitude balloon research has directly contributed to the cost-effective testing and development of nuclear-capable hypersonic glide vehicles.

Future intelligence capability: photonic sensors + quantum communication + advanced optical communication + post-quantum cryptography

China's research strengths at the intersection of *photonic sensors*, *quantum communications*[82] and *advanced optical communications*, in addition to *post-quantum cryptography*, could mean that intelligence communities, particularly the Five Eyes, could lose important capabilities and suffer from diminished situational awareness. China leads globally in *photonic sensors* (43% of world's top 10% high-impact research, 3.41 times the US), *quantum communications* (31%, 1.89 times the US), *advanced optical communications* (38%, 2.95 times the US) and *post-quantum cryptography* (31%, 2.3 times the US). Taken together, these observations increase the risk of Chinese communications going dark[83] to the efforts of western intelligence services. This reduces the capacity to plan for contingencies[84] in the event of hostilities[85] and tensions.

China has reportedly built the physical infrastructure to claim the world's largest quantum communication network,[86] and has even established *quantum communication* with moving drones[87] and satellites.[88] As with many things, the risk is cumulative—the risk increases as China leads in both cryptography resistant to decryption by quantum computers and the ability to share encryption keys via *quantum communication*. One mitigating factor is the current US lead in *quantum computing* (34% of world's top 10% high-impact research output, 2.26 times China).

The power of artificial intelligence: AI algorithms and hardware accelerators + electric batteries

Weapons and intelligence systems driven by AI will increasingly determine the outcome of conflicts and tip the balance in the race for military supremacy.[89] The Javelin missile targeting system[90] and the F-35 fighter jet[91] rely on advanced algorithms running on fast, powerful and energy-efficient hardware. Similarly, AI is used for the first pass of sifting through mountains of signals intelligence[92] to find potentially valuable insights,[93] and for the fusion of datasets,[94] which are then scrutinised by human analysts.[95]

China is leading *artificial intelligence (AI) algorithms and hardware accelerators* (37% of world's top 10% high-impact research output, 2.76 times the US). Lower power-consumption hardware means the possibility of training more sophisticated AI models for use in portable military hardware, and lowering power costs by an order of magnitude. Paired with better *electric batteries*—again China is the global leader (a striking lead of 65%, 5.51 times the US)—this enables the deployment of more sophisticated military hardware[96] to soldiers on the battlefield.[97] Research innovations and scientific breakthroughs will continue to translate into increasingly sophisticated AI-enhanced equipment in the hands of military commanders around the world (at least in those countries investing in, or buying, such technologies). On the current trajectory, as the perceived capability gap narrows in the years and decades to come, China's cost calculations for taking Taiwan by force will be lower, and the risk of major-power conflict could rise.[98]

Military use of drones: drones, swarming and collaborative robots + autonomous systems + electric batteries + directed-energy technologies

Drones have a somewhat nebulous public image owing to their wide variety of use cases. Some think first of state-of-the-art remotely operated fixed-wing aircraft such as the Boeing Ghost Bat.[99] Others think of small quad-copter drones used for surveying and aerial photography. A drone mimicking the outline and movement of a bird was recovered in Pakistan, and was reportedly used to video unsuspecting insurgents.[100]

The military use of drones, and the distinct and asymmetrical military and intelligence advantage they can provide to those who excel in drone warfare, highlights where some of the competition for future drone capability is most intense in the *Critical Technology Tracker*. Flying drones in the vicinity of military exercises and over sensitive defence locations creates unparalleled intelligence-collection opportunities for adversaries.[101]

But the real game changer for military purposes comes in the form of swarming and collaborative drones. Zhejiang University in China recently demonstrated drone swarms autonomously navigating through complex environments and using computer vision algorithms to identify humans.[102] This university ranks highly in many technologies and was also rated high risk by ASPI's *China Defence University Tracker*.[103] The breakthrough lies in the ability to share information collected from the sensors in each drone with the entire swarm, resulting in vastly superior situational awareness.[104] More advanced battery technology enables such drones to operate over longer distances, for greater lengths of time, and to house more sophisticated systems.

China has a 3.5 times greater share of high-impact publications in *drones, swarming and collaborative robots* and five of the world's top 10 institutions. Likewise, for *electric batteries*, China has a 5.5 times lead over the US in its share of high-impact research, and eight of the top 10 institutions are based in China. The only technology within this application in which China doesn't eclipse its rivals is *autonomous systems*, for which China's lead is a more modest 1.2 times, and in which far fewer field-leading institutions are China-based (three out of 10 are China-based; four out of 10 are US-based).

Defending against swarming drones is a huge challenge. In recent years, there's been an increasing focus on using directed electromagnetic pulses to destroy drones' electronics, delivered from both small[105] and large form factor devices.[106] China leads in *directed energy technologies* with 2.05 times the US in high-impact publications and has seven of the world's top 10 institutions. Another approach is tricking the algorithms controlling the drone swarm such that drones collide or attack a dummy target.[107] This is known as 'adversarial AI', and the techniques for defending against such attacks sit within *protective cybersecurity technologies*, which China leads at 1.33 times the US in high-impact research and has four of the world's top 10 institutions.

Technology deep dives

This section provides in-depth analysis of our findings in three technology areas: artificial intelligence, quantum technologies and advanced materials and manufacturing. We provide brief contextual material on how the technology unlocks value, pivotal moments in the technology's development, the universities and companies producing the best research, and any noteworthy insights into funding or national strategies. For each technology area, we have included a table of the top five ranked countries and the technology monopoly risk, insights and context from the top 20 institutions, and key points from the talent tracker.

If a deep dive into these technology fields isn't for you, jump ahead to the 'Policy recommendations' section.

Artificial intelligence, computing and communications

Ten technologies sit within the *artificial intelligence, computing, and communications* category in ASPI's *Critical Technology Tracker*. AI, more than any other technology, continues to dominate the public debate. Within two months from its release by OpenAI, the online chatbot ChatGPT has acquired over 100 million regular users.[108] As a measure of its impact: it took TikTok over nine months and Instagram over 2.5 years to achieve the same user take-up. Most significantly, ChatGPT aspires to satisfy the Turing test, in which a human is unable to distinguish a chatbot-generated response from a human response. ChatGPT[109] is built on a language model trained on big data,[110] combining supervised learning and reinforced learning from human feedback. Thus, chatbots such as ChatGPT, Google's Apprentice Bard[111] and the like benefit from developments in a number of AI subcategories that we're now tracking, including *AI algorithms and hardware, machine learning* and *natural language processing* technologies.

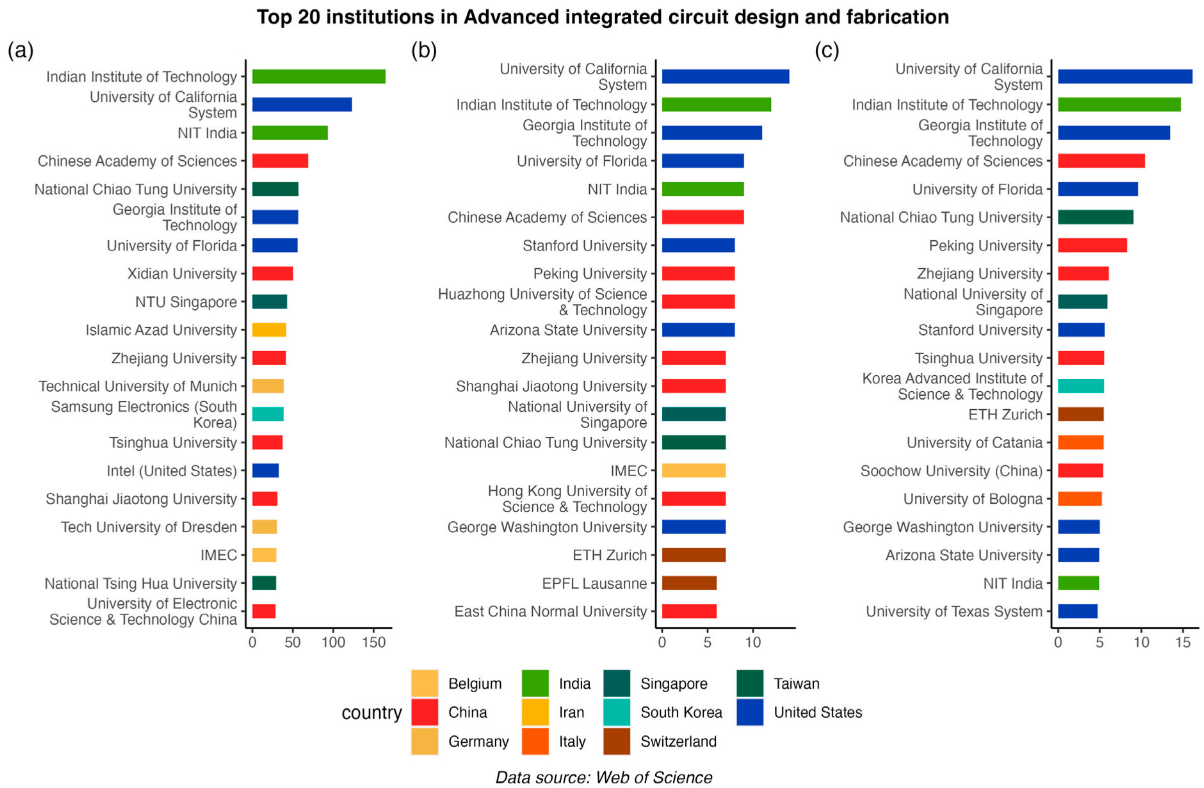
The demand for faster AI capabilities has placed AI chips[112] at the centre of the race for a tech-driven economy and boosted research. Silicon Valley technology companies are among the top performers, which shows that high-impact research spans universities and the private sector. This highlights the importance of a tech-driven ecosystem; that is, a country must have a thriving university sector and private industry to achieve and maintain the research lead.

Table 3: Top 5 country rankings: Artificial intelligence, computing and communications.

Technology	Top 5 countries					Technology monopoly risk
Advanced radiofrequency communications (incl. 5G and 6G)	29.65%	9.50%	5.18%	4.89%	4.83%	8/10 3.12 **high**
Advanced optical communications	37.69%	12.76%	5.64%	3.88%	3.48%	8/10 2.95 **medium**
Artificial intelligence (AI) algorithms and hardware accelerators	36.62%	13.26%	4.20%	4.15%	3.48%	7/10 2.76 **medium**
Distributed ledgers	28.38%	11.32%	8.94%	5.54%	4.81%	6/10 2.51 **medium**
Advanced data analytics	31.23%	15.45%	6.02%	4.19%	3.92%	8/10 2.02 **medium**
Machine learning (incl. neural networks and deep learning)	33.20%	17.93%	4.87%	3.87%	3.32%	7/10 1.85 **low**
Protective cybersecurity technologies	23.33%	16.80%	7.67%	5.71%	5.20%	5/10 1.33 **low**
High performance computing	29.31%	25.57%	6.34%	4.68%	3.98%	3/10 1.15 **low**
Advanced integrated circuit design and fabrication	24.18%	21.19%	7.16%	4.46%	3.57%	4/10 1.14 **low**
Natural language processing (incl. speech and text recognition and analysis)	25.73%	23.57%	5.74%	4.55%	3.37%	5/10 1.09 **low**

The US excels in the design and development of the most advanced semiconductor chips and has a research lead in the technology areas of *high performance computing* and *advanced integrated circuit design and fabrication*. It's worth mentioning that, while Taiwan is a semiconductor manufacturing powerhouse and is supplying over 90% of the world's advanced semiconductors, most of the chip research and design is actually conducted in the US.[113] In our data, Taiwan ranks ninth for the number of papers in the top 10% of highly cited papers for *advanced integrated circuit design and fabrication*, while the top Taiwanese institution, the National Chiao Tung University, is in sixth place (see Figure 1(c) below).

Figure 1: Top 20 institutions in advanced integrated circuit design and fabrication by (a) the weighted number of publications (b) H-index and (c) the weighted number of publications within the top 10% of highly cited publications. Note that some institutions which were equally ranked at 20, were truncated for clarity.



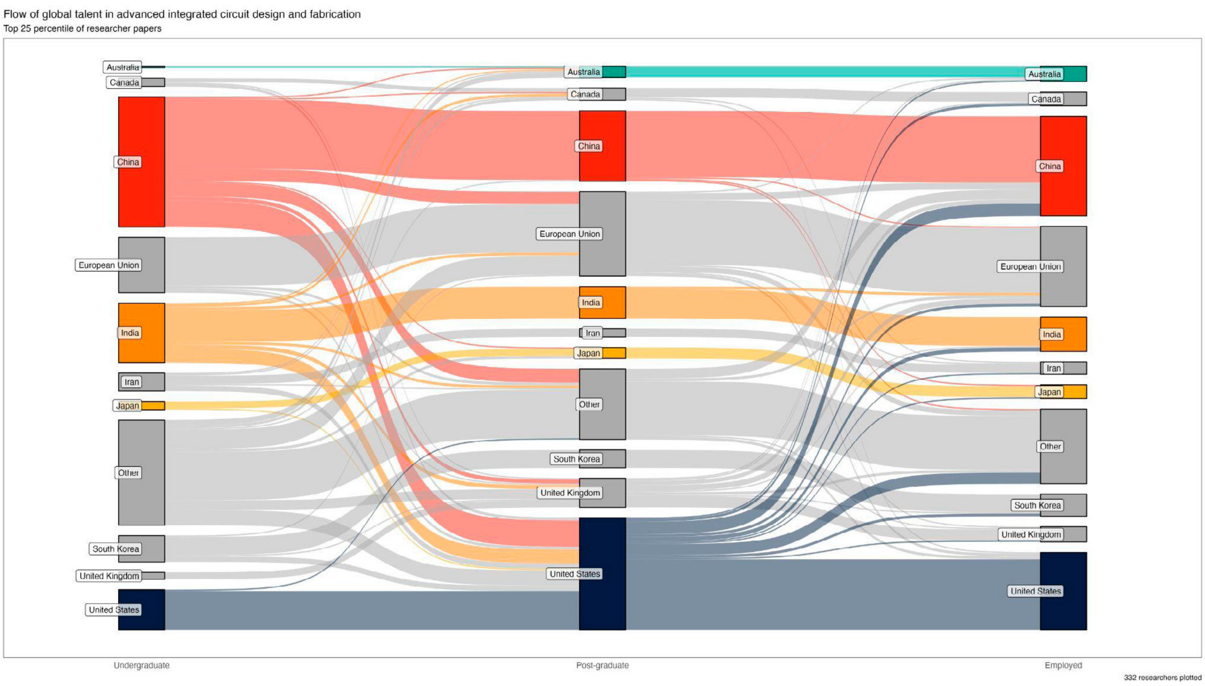
Within the *AI, computing, and communications category*, *advanced integrated circuit design and fabrication* has the highest number of countries represented and is ranked low on our tech monopoly risk measure. Four European countries (Belgium, France, Germany and Italy), Canada, India, Singapore, South Korea, Switzerland and Taiwan in addition to China and the US appear in the top 20 institutions. The University of California system, the Georgia Institute of Technology and the University of Florida are among the top institutions, together with the Indian Institute of Technology (IIT) in India.

Technology companies such as Taiwan Semiconductor Manufacturing Corporation (TSMC) and Samsung Electronics are the world's major suppliers of consumer-grade and advanced integrated circuits, and are supported by local institutions such as the National Chiao Tung University[114] and the Korea Advanced Institute of Science & Technology respectively.[115]

In 1984, the Belgian Interuniversity Microelectronics Centre (IMEC) was founded by a group of young semiconductor researchers inspired by the Silicon Valley model as an R&D research centre[116] and focused on developing silicon processing and fabrication for different generations of complementary metal-oxide-semiconductor technologies. Today's IMEC employs more than 5,000 researchers and is a strong international player in semiconductor and integrated circuit fabrication. IMEC owns significant intellectual property, and the funding from major collaborations with international companies currently exceeds the government funding received from the regional Flemish Government.[117] IMEC features among the top 20 institutions in *advanced integrated circuit design and fabrication* technology (14th by H-index). STMicroelectronics is a European company owning several wafer fabrication plants in the University of Grenoble and the University of Catania, which explains the presence of these two universities in *advanced integrated circuit design and fabrication* technology.[118]

According to the Semiconductor Industry Association (SIA), the US is expected to experience a shortage of design engineers by 2030 due to a number of factors, including a yearly loss of 2% of its experienced design engineers and a strong reliance on international students (lower enrolments).[119] The cost of advanced chip design almost doubles with each generation of advanced chip design and, while the proportion of public investment in semiconductor chip design companies in the US was estimated to be around 13%, governments in Europe, China, Taiwan, Japan and South Korea have boosted funding for local semiconductor design capabilities (an average of over 30% public investment).[120] In addition, South Korea, China and India offer lucrative tax incentives for semiconductor R&D companies. Our talent-flow data for *advanced integrated circuit design and fabrication* technology shows that the US has a significant talent intake from China, India, South Korea and other countries for postgraduate training, of whom a fraction choose to stay in employment, in agreement with the SIA findings. In an effort to counter China and bolster its local semiconductor industry, the US Government announced the CHIPS Act with a US$280 billion package and around US$11 billion for semiconductor R&D design, packaging and manufacturing.[121] While the CHIPS Act will strengthen the local semiconductor manufacturing industry, it's unclear how much the Act would match the level of public spending in semiconductor R&D design to the competition. The US private sector spent US$40 billion on design R&D in 2021 alone.[122]

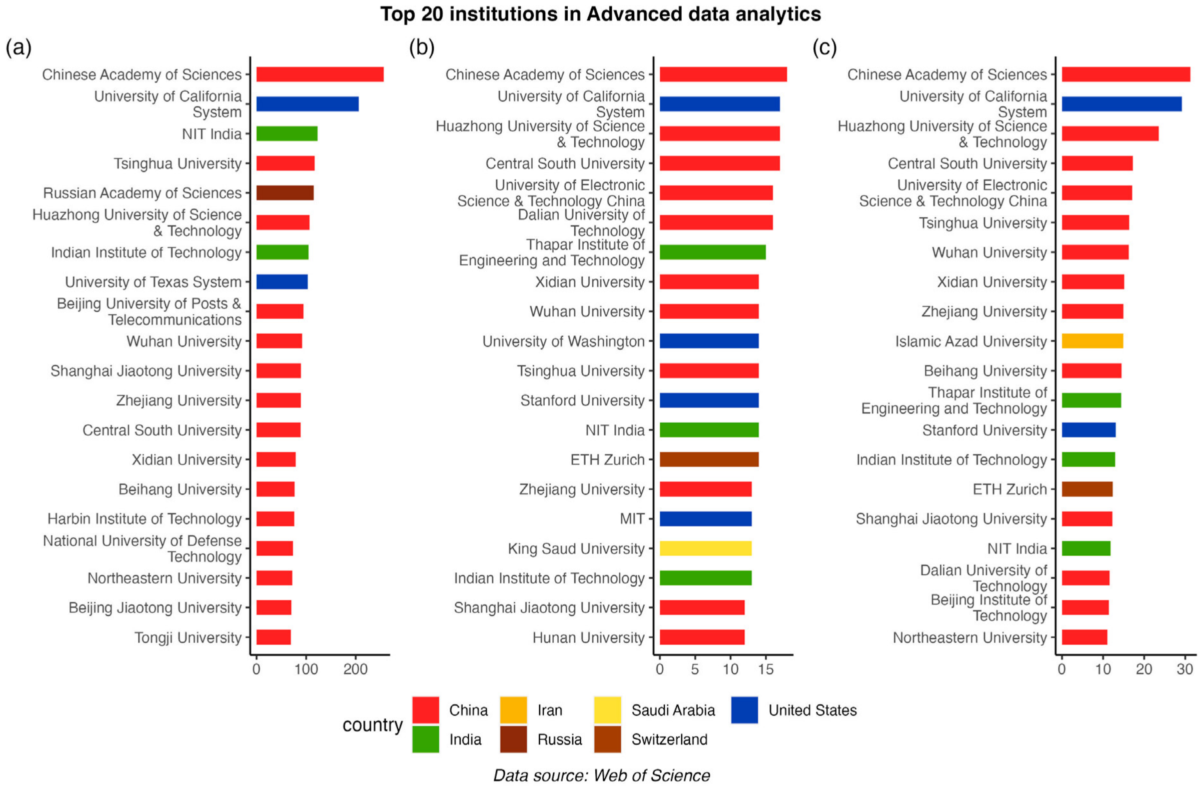
Figure 2: Flow of global talent in advanced integrated circuit design and fabrication.



There's a close race between the US and China for supremacy in the technology areas *machine learning* (China leads) and *natural language processing* (the US leads). These technologies are heavily invested in by the Silicon Valley ecosystem and other technology companies. However, China has a research lead in the remaining technology areas: *advanced data analytics*, *advanced optical communications*, *advanced radiofrequency communications*, *artificial intelligence algorithms and hardware accelerators*, *distributed ledgers*, *machine learning*, and *protective cyber security technologies*.

In *advanced data analytics*, China is the leading country and claims 13 of the top 20 institutions (Figure 3). This technology is important because it underpins the ability to derive novel and valuable insights from large datasets and deliver those in near real time to, for example, soldiers on the battlefield[123] or pilots in the sky.[124] From a commercial perspective, maintaining a lead in this area underpins the business model of search companies such as Google, ByteDance and Baidu.[125]

Figure 3: Top 20 institutions in advanced data analytics by (a) the weighted number of publications (b) H-index and (c) the weighted number of publications within the top 10% of highly cited publications. Note that some institutions which were equally ranked at 20, were truncated for clarity.



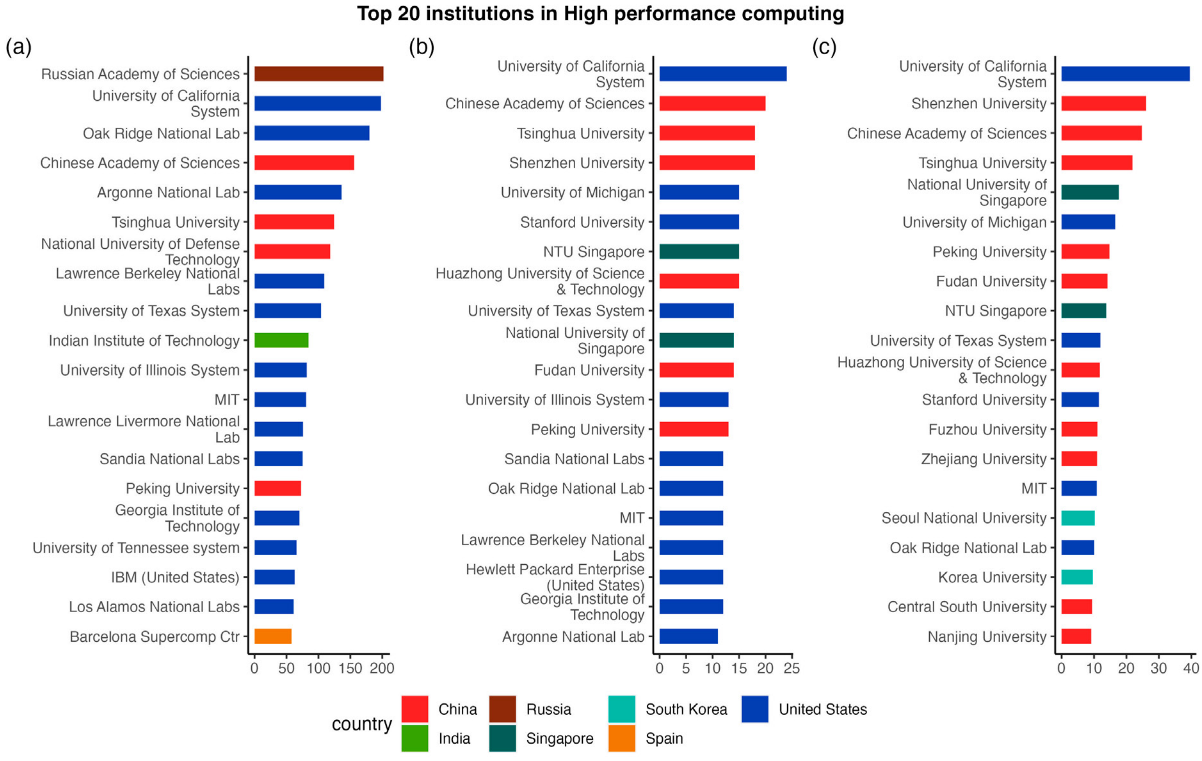
The top institutions in *advanced data analytics* include the Chinese Academy of Sciences, the University of California system (which comprises 10 campuses scattered across California)[126] and the Huazhong University of Science and Technology. Depending on the quality metric used (see the methodology from page 10 for an explanation), either two or four US universities are in the top 20 institutions. The University of California system and Stanford University feature in the top 20 institutions of both quality metrics, whereas the University of Washington and Massachusetts Institute of Technology (MIT) join the list based on the H-index metrics. India has three institutions in the top 20: the Thapar Institute of Engineering and Technology, NIT India and the Indian Institute of Technology. Switzerland, Saudi Arabia, Australia and Iran each have one institution in the top 20.

The University of California system is the only institution to rank among the top 20 institutions in all AI categories. It's the first or second ranked US university in all technologies within the *AI, computing, and communications category*, coming up as the top institution in *machine learning*, *high performance computing* and *advanced integrated circuit design and fabrication*. With Silicon Valley within its borders, the state of California is a tech hub, conducive to research commercialisation. With 10 campuses, the University of California (UC) system combines prestigious institutions such as UC Berkeley, UC Los Angeles, UC San Francisco and UC Davis. In addition, the University of California manages and operates one national laboratory for the Department of Energy—the Lawrence Berkeley National Laboratory (also known as the Berkeley lab)—and also hosts the Lawrence Livermore National Laboratory.[127] This combination of industry and research institutions creates a vibrant tech ecosystem in which critical technologies can thrive.

Two Chinese universities follow closely behind the UC system; the Chinese Academy of Sciences and Tsinghua University both rank among the top 20 institutions in nine out of the 10 AI technologies from their publications within the top 10% of highly cited papers. Huazhong University of Science and Technology and Zhejiang University both rank within the top 20 institutions in eight out of the 10 AI technologies from their publications within the top 10% of highly cited papers. The Indian Institute of Technology is ranked among the top 20 institutions in seven out of the 10 AI technologies from its publications within the 10% of highly cited papers. An interesting finding is the presence of Singapore in all technologies in the AI category except for *advanced data analytics*, especially within the quality metrics: Nanyang Technological University (NTU) and the National University of Singapore are represented in six and five of the 10 AI categories, respectively. Singapore has the third highest GDP per capita[128] and is one of the Asian tigers[129] focused on critical technologies.

US tech companies are also well represented in AI: Google (1st in *natural language processing*), Microsoft (6th in *natural language processing* by H-index), Facebook (13th in *natural language processing*), Hewlett Packard Enterprise (14th in *high performance computing*) and IBM (both the US and the Switzerland arms rank 11th in *AI algorithms and hardware accelerators*, combining these two institutions together may bump their H-index higher). Another noteworthy finding is the strong representation of US Department of Energy (US DoE) national labs in *high performance computing* (see Figure 4): Sandia National Laboratories, Oak Ridge National Laboratory, Lawrence Berkeley National Laboratory and Argonne National Laboratory are in the top 20 institutions when measured using the H-index metrics.

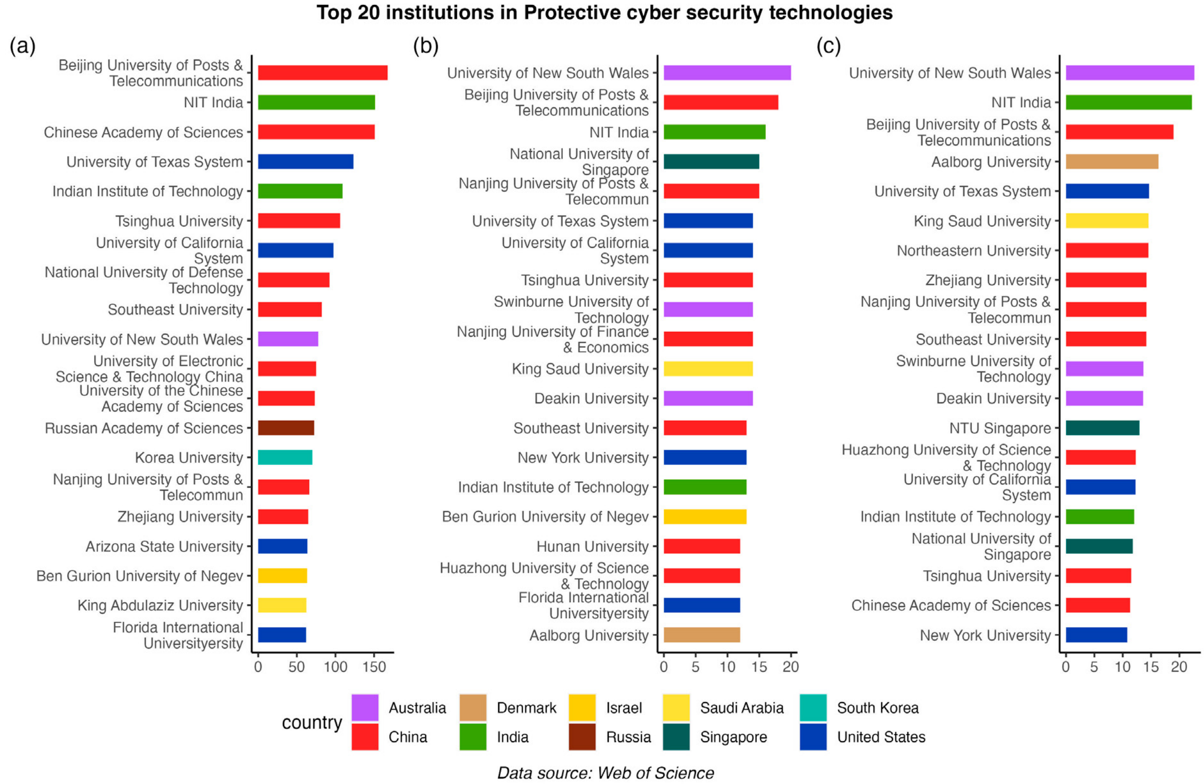
Figure 4: Top 20 institutions in high performance computing by (a) the weighted number of publications (b) H-index and (c) the weighted number of publications within the top 10% of highly cited publications. Note that some institutions which were equally ranked at 20, were truncated for clarity.



Data source: Web of Science

Despite its small population, Australia is strongly represented in the top 20 institutions for *protective cyber security technologies*: the University of New South Wales ranks first, and Swinburne University of Technology and Deakin University are also in top 20 institutions (Figure 5). Protective cybersecurity technologies are focused on systems, technologies and hardware designed for cybersecurity. This includes, for example, the automated detection of malware using software signatures, behavioural analysis of computer network activity to detect data exfiltration by sophisticated (that is, nation-state) actors, protection against denial of service attacks, and the ability to detect and block botnet traffic.

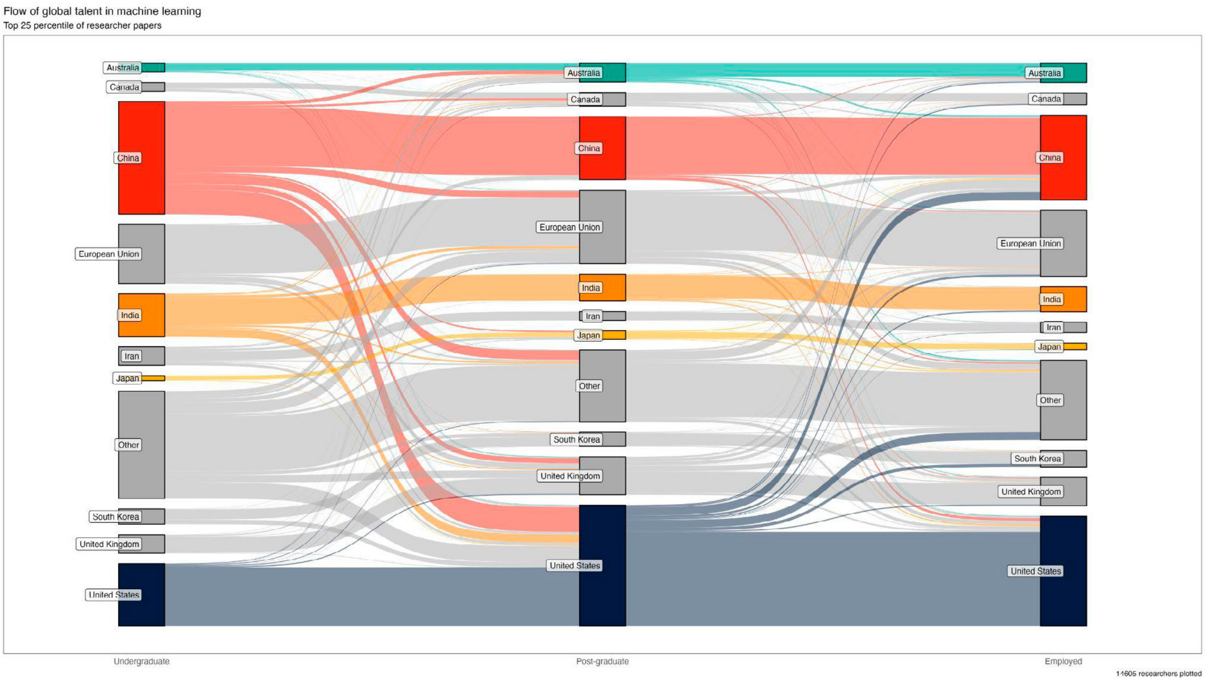
Figure 5: Top 20 institutions in protective cybersecurity technologies by (a) the weighted number of publications (b) H-index and (c) the weighted number of publications within the top 10% of highly cited publications. Note that some institutions which were equally ranked at 20, were truncated for clarity.



The US is generally good at attracting migration from overseas into its postgraduate training programs in all technology areas within the *AI, computing, and communications category.* Significant talent pools migrate from India and China to work in the US. Figure 6 shows the flow of talent for the *machine learning* category, which has the largest number of papers (half a million). This dataset tracks 14,525 researchers from the top 25% of highly cited papers and it shows that, after the postgraduate level, the US loses a significant proportion of the talent while making an overall gain from the number of researchers it trains at the postgraduate level. A significant proportion of US trained researchers choose to move to China, South Korea, the EU and other countries.

China, on the other hand, makes a talent gain into employment across all technologies in the AI category (for example, Figure 6 shows that inflows to China at the employment level are greater than outflows at the postgraduate level). Australia appears to do well in attracting talent for training at the postgraduate level and retaining those people in future employment in all AI categories, as does the UK. India has a significant brain drain in *AI algorithms and hardware accelerators*, as many people opt to do their postgraduate training in the US, Singapore and Europe, but the brain drain in *machine learning* is significantly less, as India retains most of its postgraduate trained talent through employment. South Korea loses some of its undergraduates to the US in both *AI algorithms (and hardware accelerators)* and *machine learning* but eventually manages to retain most of its postgraduate trained talent into employment. Almost half of postgraduates from China leave to train elsewhere, mostly in the US followed by the UK, the EU, Australia and Canada. Many return home for employment (alongside inflows of foreigners moving to China for employment), but China doesn't retain all of that talent.

Figure 6: Flow of global talent in machine learning (top 25% of research papers).



The overarching question is whether the US can overturn China's potential future leadership in AI. The US is on par with China in its employed talent in *advanced data analytics*[130] and *protective cybersecurity*. In line with the US's sustained leadership in *advanced integrated circuit design and fabrication*, *high performance computing* and *natural language processing*, the proportion of global talent employed in the US exceeds that of China's. On the other hand, the fraction of global talent employed in China on *artificial intelligence algorithms and hardware accelerators* is more than twice the fraction of global talent in the US in this category but, together with other countries leading in this technology area (the UK, South Korea, Singapore and Europe), some of the interdependencies and supply-risk issues can be mitigated in a global effort.[131]

A US–Europe alliance, for example, in *advanced integrated circuit design and fabrication* would hinder China's aim to achieve supremacy.[132] For device nodes below 90-nanometres, only two companies can supply the relevant photolithography system: Nikon (Japan) and ASML (the Netherlands).[133] Below 5-nanometre device nodes, ASML has the monopoly for extreme ultraviolet (EUV) lithography and reigns supreme as a key processing tool supplier for leading-edge chips. In *advanced radiofrequency communications* and *distributed ledgers*, Europe is on par with or exceeds China's global talent and has the potential to play a greater leading role in these critical technologies.[134]

Quantum technologies

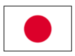
Quantum mechanics was born from a series of scientific breakthroughs in the early 1900s and ultimately evolved into modern quantum mechanics.[135] Its concepts have brought so much to our daily lives, from understanding semiconductor devices to future quantum computers. Quantum technology is currently present on governments'[136] and country alliance[137] lists that outline which emerging technologies governments around the world see as 'critical' to their future. Once a technology is named as 'critical', the issue of national security becomes important and limits the prospects of international collaboration.[138] Quantum technology is also supported by over $30 billion of public

R&D funding internationally.[139] China is estimated to have the highest level of public funding allocated to quantum technologies (over US$14 billion)[140] followed by the EU (US$7.2 billion) and countries such as Germany, France, the Netherlands and Sweden are among the top funded European nations. Israel is the highest investor on a per capita basis. Australia is also part of this international effort after a A$111 million funding announcement in 2021,[141] including for its National Quantum Strategy and new National Quantum Advisory Committee.[142]

EU countries are among the top 5 highest performing countries in all quantum technologies. As a bloc, the EU is a strong competitor to China in all quantum technologies, including *post-quantum cryptography*, in which the US is trailing China by a larger margin than in other quantum technology areas (Figure 11).

Big tech companies such as IBM, Google, Microsoft, Alibaba and Amazon are the largest private investors, especially in the US, where over 80% of funding for quantum research is from the private sector. Private investments were around $1.4 billion globally in 2021 and were expected to be over $2 billion in 2022,[143] with the majority of this funding tied up in start-up companies focusing on quantum hardware, notably in quantum computing.

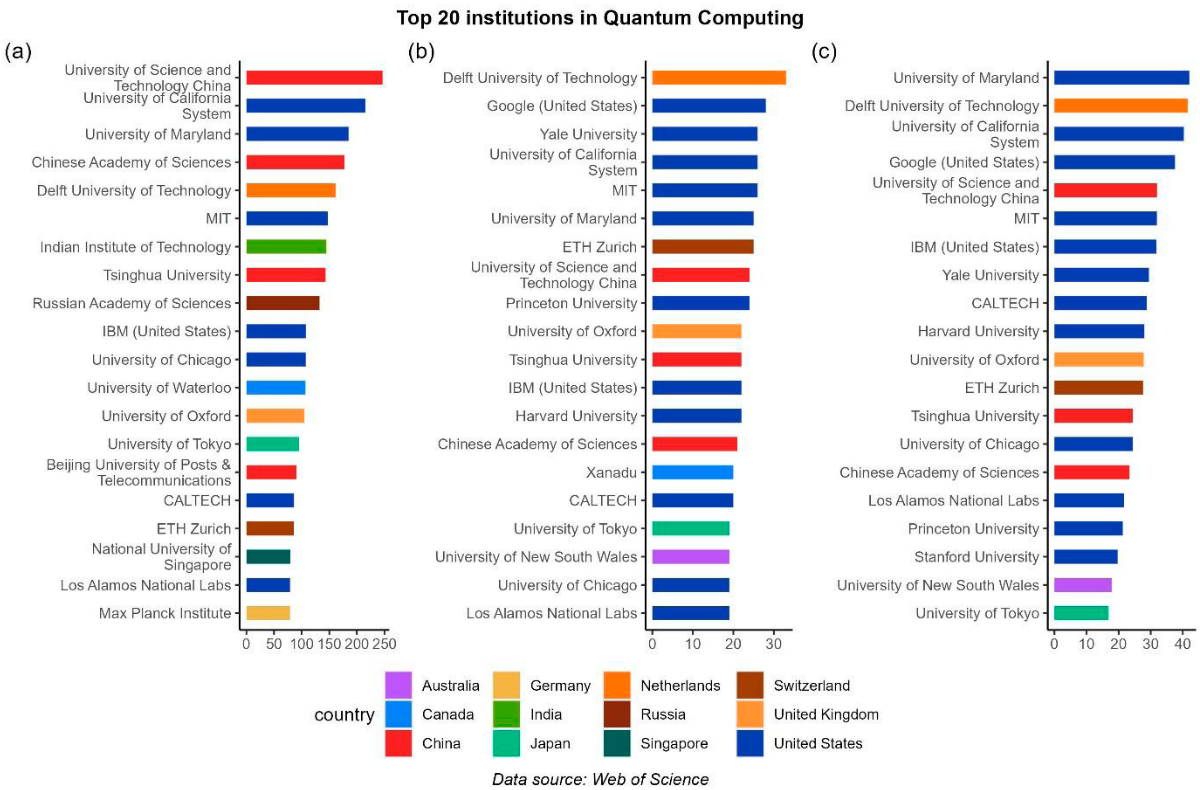
Table 4: Top 5 country rankings: Quantum technologies.

Technology	Top 5 countries					Technology monopoly risk
Quantum computing	 33.90%	 15.03%	 6.11%	 5.52%	 4.13%	8/10 2.26 **medium**
Post-quantum cryptography	 30.98%	 13.30%	 6.41%	 4.73%	 3.69%	4/10 2.30 **low**
Quantum communications (incl. quantum key distribution)	 31.47%	 16.68%	 7.58%	 6.45%	 3.81%	5/10 1.89 **low**
Quantum sensors	 23.70%	 23.27%	 7.76%	 4.29%	 4.20%	2/10 1.02 **low**

There are four quantum technology areas: *quantum computing*, *quantum communications*, *post-quantum cryptography* and *quantum sensing*,[144] which are included in the *Critical Technology Tracker* (see above).

Figure 7 shows the top 20 institutions in *quantum computing*, which is clearly an area of US dominance, especially in the number of US institutions (11–12/20 of the top institutions) represented in our quality metrics. Three tech companies are in the top 20 institutions by the H-index: Google, IBM and Xanadu. Google and IBM are established tech companies set to offer cloud quantum computing services, and Google (in partnership with IonQ) is already offering cloud access to an 11-qubit system.[145] To date, the world's largest quantum computer is IBM's Osprey, a 433-qubit computer, breaking IBM's previous record of 127 qubits with the Eagle quantum processor.[146] Prior to this, Google was the first group to define quantum advantage (over classical) with its 53-qubit Sycamore processor with a record processing time of 200 seconds for a task that takes 10,000 years on a classical supercomputer. Of note, the high qubits (>50) are achieved with superconducting components that require cryogenic temperatures. Room-temperature quantum computers have lower operational costs but currently offer single-digit qubits.[147] Xanadu is a Canadian spinoff company championing the world's first photonic quantum computer (216 qubits), offering cloud access.[148] There's still significant scaling required before these companies are able to offer quantum computers that reliably outclass classical computers in useful applications. Estimates suggest that around a million qubits would be required for practical applications such as easily breaking current encryptions or optimising financial markets.[149] Setting aside questions of feasibility, Google has set a target to reach this scale by the end of the decade.[150]

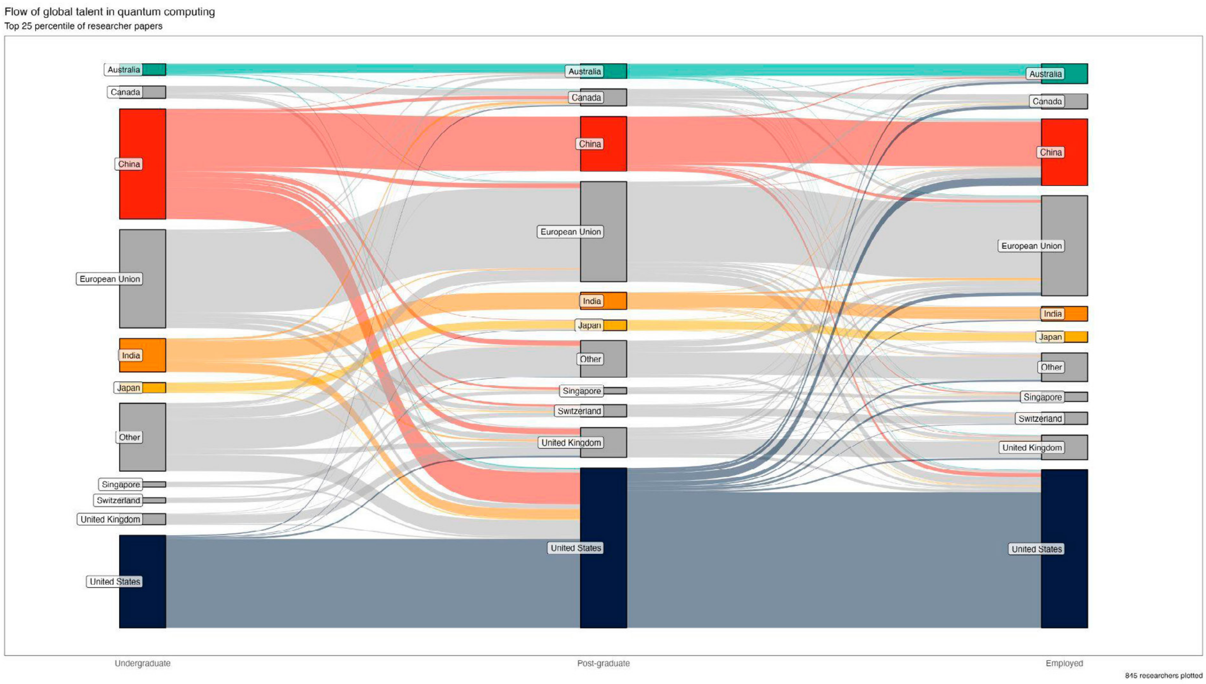
Figure 7: Top 20 institutions in quantum computing by (a) the weighted number of publications (b) H-index and (c) the weighted number of publications within the top 10% of highly cited publications.



The top institutions for *quantum computing* are the Delft University of Technology in the Netherlands (H-index) and the University of Maryland (top 10% of highly cited papers). One of the most important scientific breakthroughs in 2012 was the discovery of the Majorana fermion quantum states[151] (hypothesised in 1937 by Ettore Majorana), which has promising applications in quantum computing. The significance of these exotic quantum states translated to an international flurry of activities in academia and industry with Microsoft setting up the Microsoft Quantum Lab Delft at the Delft University of Technology in 2019.[152] However, the quantum-computing research community was rocked in 2021 by the retraction of this seminal paper, citing 'insufficient scientific rigour' in the original data analysis published in 2012.[153] We filtered out records with Majorana fermions to understand the impact that this retraction of research has on the institution's ranking and found that only 30 out of the 462 research papers by Delft University of Technology were on Majorana fermions. Most importantly, once all Majorana papers were taken out of the dataset,[154] the ranking of the university in the top 20 institutions remained unchanged. This highlights the leadership of the university in *quantum computing*. Delft University of Technology makes the list of the top 20 institutions across all quantum technologies in the *Critical Technology Tracker*, and its prime position is consistent with the high level of investment in quantum technology by the Netherlands.[155]

The lead held by the US and Europe is also evident in our workforce analysis (Figure 8), where, by a large margin, these two entities are able to attract and retain a large amount of global talent working in quantum computers. For a field contending with a growing talent gap, such a talent advantage places Europe and the US in an especially strong position.[156]

Figure 8: Flow of global talent in quantum computing (top 25% of research papers).



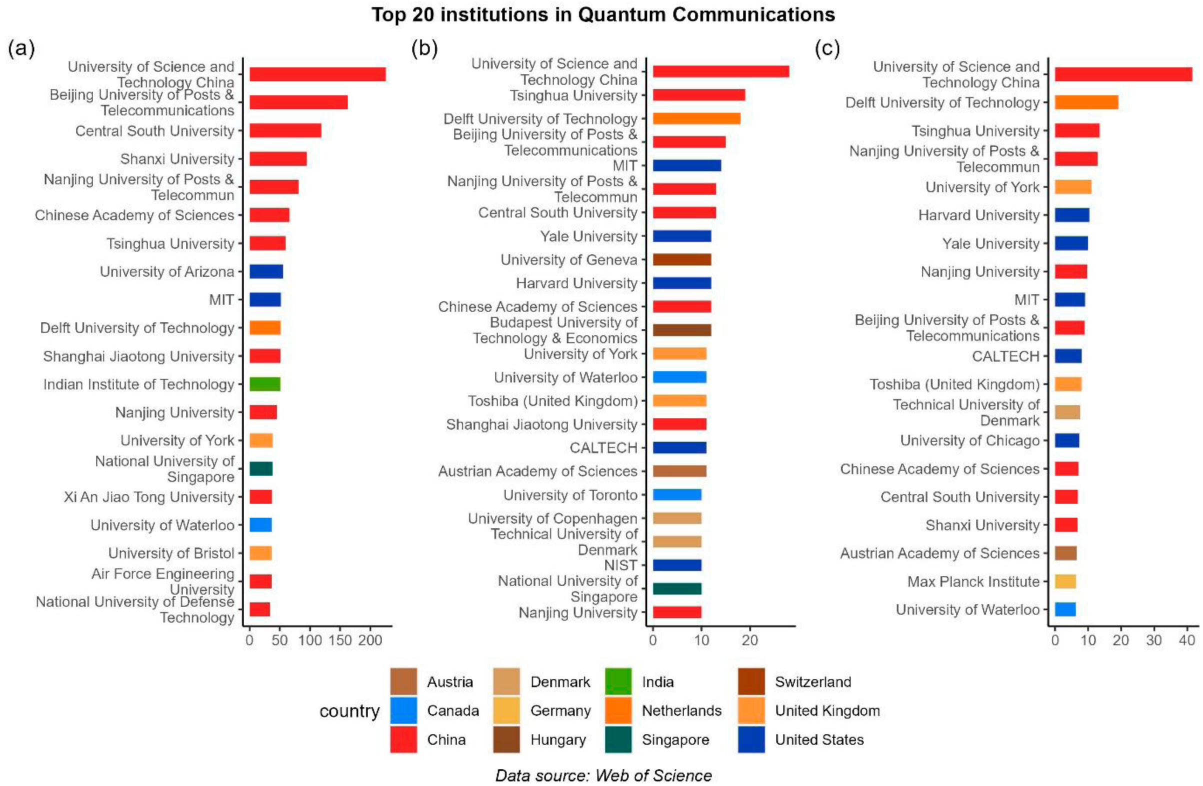
With a historical predominance in quantum communication (see box), China's efforts in quantum computing gained traction later especially after its clear mention among the major science and technology projects announced in 2016.[157] In 2021, the University of Science and Technology (USTC) put out two papers on a photonic quantum computer[158] and a superconducting quantum computer,[159] both from teams led by Jian-Wei Pan,[160] clearly indicating a change of pace in China's ambition to gain dominance in quantum computing. While *quantum computing* is currently China's weakest quantum technology, two Chinese universities are the only other institutions (apart from the Delft University of Technology) to be ranked among the top 20 institutions for all quantum technologies: USTC and Tsinghua University. USTC ranks higher across all quantum technologies.

China’s lead in quantum communications

Quantum communications is an area of strength for China. USTC is the top institution irrespective of the quality metrics, and a total of eight out of 20 top institutions are based in China (see Figure 9). Tsinghua University and Delft University of Technology in the Netherlands occupy the second and third places depending on the quality metrics. China’s lead in *quantum communications* is especially prominent in the proportion of publications in the top 10% of highly cited papers. China’s quantum research was spearheaded by the Xiangshan Science Forum for quantum information in Beijing in 1998, which resulted in experimental research in quantum information within several Chinese universities and research institutes, including USTC, Shanxi University and the Chinese Academy of Sciences’ Institute of Physics.[161]

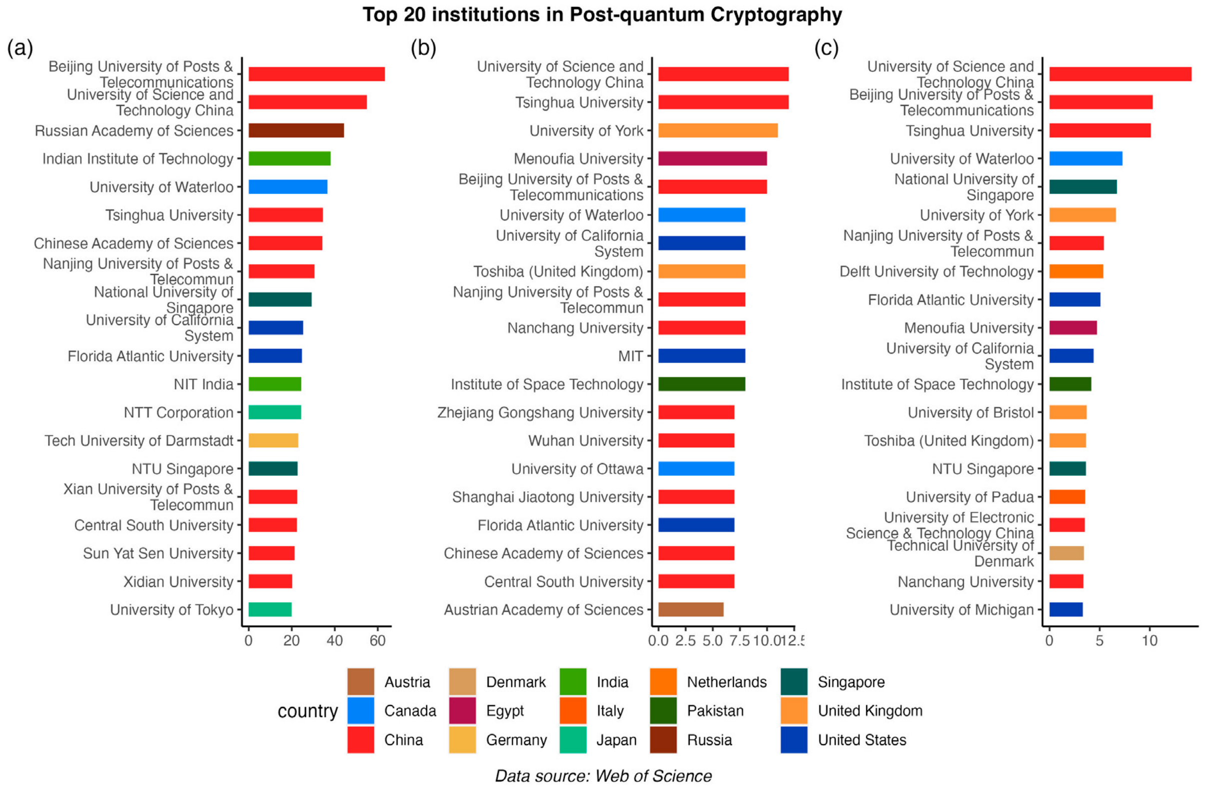
The Edward Snowden leaks exposed China’s security vulnerability to US intelligence capabilities in 2013 and triggered China’s desire to secure its communications.[162] This enabled USTC scientist Jian-Wei Pan to demonstrate the potential of *quantum communications* to Xi Jinping and other Politburo members, and he became known as the founder of Chinese quantum science. In China’s Thirteenth Five-Year National Science and Technology Innovation Plan announced in August 2016,[163] the CCP strengthened its quantum strategy further by listing *quantum communications* and computing as major science and technology projects for advances by 2030. USTC demonstrated China’s dominance in *quantum communication* by building the first fibre-based ‘Beijing–Shanghai Quantum Secure Communication Backbone’ in 2013, connecting Beijing, Shanghai, Jinan Hefei and 32 reliable nodes over a total transmission distance of more than 2,000 kilometres.[164] The strength of *quantum communications* is that it ensures secure communication due to quantum entanglement, which effectively ensures that any quantum information is modified when observed. This effectively makes it difficult to amplify quantum signals in the conventional way used for current optical communications. Pan’s research team made another significant breakthrough in 2017 by using the first quantum satellite (*Micius*, launched in 2016), and the free space reduced attenuation to transmit image and sound information using quantum keys over 7,600 kilometres between Austria and China.[165] The Austrian Academy of Science is also another strong institution for quantum research: quantum researchers have been working there on fundamental quantum optics for over two decades, and it was where Jian-Wei Pan trained as a PhD student in Anton Zeilinger’s[166] group (obtaining his PhD in 1999).

Figure 9: Top 20 institutions in quantum communications by (a) the weighted number of publications (b) H-index and (c) the weighted number of publications within the top 10% of highly cited publications.



The US and the UK are ranked second and third in *quantum communications*. Among the top 20 institutions, five or six US institutions are distinguishing themselves in the quality metrics. Harvard University, Yale University, MIT and Caltech take the top spots (their order depends on the quality metrics), and the National Institute of Standards and Technology (NIST) is the only non-university US institution ranked in the top 20 institutions. The only company making it in the top 20 in *quantum communications* is the Japanese company Toshiba, and this is due to output from its R&D labs in the UK, which include the Cambridge Research Laboratory and the Telecommunications Research Laboratory.

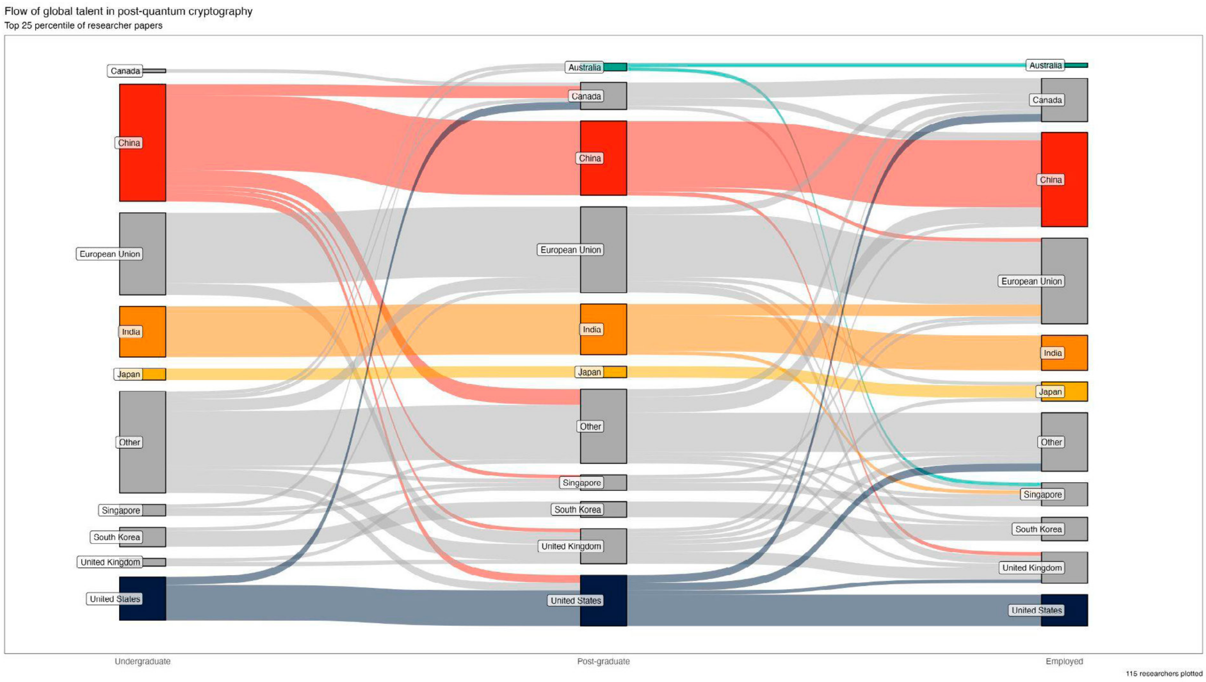
Figure 10: Top 20 institutions in post-quantum cryptography by (a) the weighted number of publications (b) H-index and (c) the weighted number of publications within the top 10% of highly cited publications. Note that some institutions which were equally ranked at 20, were truncated for clarity.



Post-quantum cryptography is a relatively small subset of our *Critical Technology Tracker* dataset but is becoming an important critical technology due to advances in *quantum computing*. The security of our current network transactions relies on the RSA 2048 encryption keys for network security and is hard to crack with current computers within a reasonable time frame.[167] The innate ability of quantum computers to solve complex problems and factor large semiprime numbers can crack the current cryptography system in an exponentially faster time frame compared to classical computing and calls for post-quantum cryptography that's resilient to security threats in a quantum computing world. This must be implemented well ahead of developments in *quantum computing* to mitigate the risk of 'harvest now, decrypt later' strategies.[168]

The *Critical Technology Tracker* shows, that while China is leading on *post-quantum cryptography* technology (with six to eight institutions out of the top 20 institutions; see Figure 10(c) of top 10% of highly cited papers), this is a low-tech monopoly risk with strong equal representations from the US, UK and Europe (three institutions each). Of note, two companies stand out in the top institutions: the Japanese NTT Corporation, which ranks 15th in the top 10% from highly cited papers, and Toshiba (again, the UK arm). This is another technology area in which even though the US is distinctly weaker in terms of its research and talent, Europe is on par with China in terms of employed talent and a Europe–US alliance can change the tech order.

Figure 11: Flow of global talent in post-quantum cryptography (top 25% of research papers).



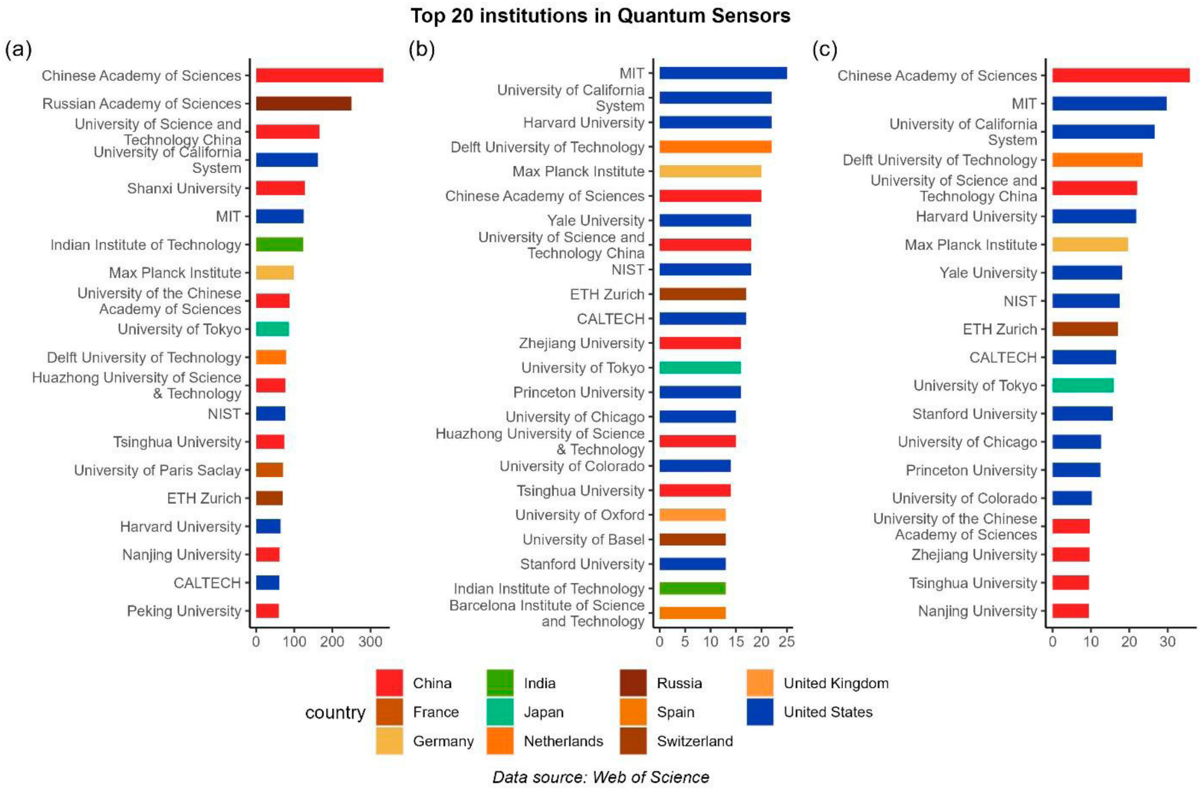
In our dataset, the top institutions in post-quantum cryptography are USTC and Tsinghua University in China. An early release of a paper that's yet to be peer-reviewed was posted on ArXiv (an open-access archive for research papers hosted by Cornell University) in late December 2022 with lead and last authors from Tsinghua University (a 'last author' is often the head of a research team), claimed to have been able to crack RSA 2048 encryption under certain conditions with a 372-qubit superconducting quantum computer.[169] However, experts have expressed doubt over the validity of that claim, asserting a significant underestimation of the challenges on both the classical and quantum sides.[170]

Quantum sensing is the quantum technology that's already seen the commercialisation of the first generation of quantum sensors in the form of atomic clocks and superconducting quantum interference devices (SQuIDs). Australia has its own success story in this field with the LANDTEM, which uses high-temperature superconductor SQuIDS[171] for mineral prospecting because of their high sensitivity to magnetic fields. The second generation of quantum sensors is being developed in parallel with advances in other quantum technologies as it exploits decades of basic research in optical physics and condensed matter physics.

The applications of *quantum sensors* are enormous, ranging from precision timing (vital to the stability of energy grids) and next-generation positioning (enabling the satellite-free navigation of defence assets) to biotechnology (medical imaging leading to early cancer detection) and mineral prospecting (gravity sensors that can explore the passive fields from mineral deposits to gas and oil deposits).[172] Most importantly, the interconnection of different technologies becomes clear as breakthroughs in quantum sensors benefit quantum communications and quantum computing and vice versa.

The US is leading in *quantum sensors*, in which 10 US institutions dominate the top 20 institutions. MIT and the University of California system are vying for the first place (Figure 12). The country quality metrics place the US ahead of China on the H-index but neck-to-neck in the fraction of papers in the top 10% of highly cited papers. Germany is ranked third in the country ranking; the Max Planck Institute (ranked 7th) is the top ranked German institution in *quantum sensors*. China has five institutions among the top 20 institutions, and the Chinese Academy of Sciences ranks first with the highest number of publications within the top 10% of highly cited papers but ranks lower in the H-index. The Netherlands' Delft University of Technology is again ranked highly, coming in at fourth in the top institutions on the H-index and the top 10% of highly cited papers, respectively.

Figure 12: Top 20 institutions in quantum sensors by (a) the weighted number of publications (b) H-index and (c) the weighted number of publications within the top 10% of highly cited publications.



Advanced materials

Advanced materials encompass all the materials that have been engineered to display superior and novel properties compared to their un-engineered properties. Progress in the field of advanced materials has the potential to shape the future of technological-advance-generating outputs (including new technologies and materials)[173] with high performance characteristics that could, for example, be more cost-effective, energy efficient, durable, lightweight, fire resistant or smaller. There are clear gains to be made from advances in this area, and some governments, whether from a manufacturing,[174] trade[175] or defence and national security perspective,[176] are putting strategies and plans in place to take greater advantage of progress and innovations occurring in the field of advanced materials.

Table 5: Top 5 country rankings: Advanced materials and manufacturing.

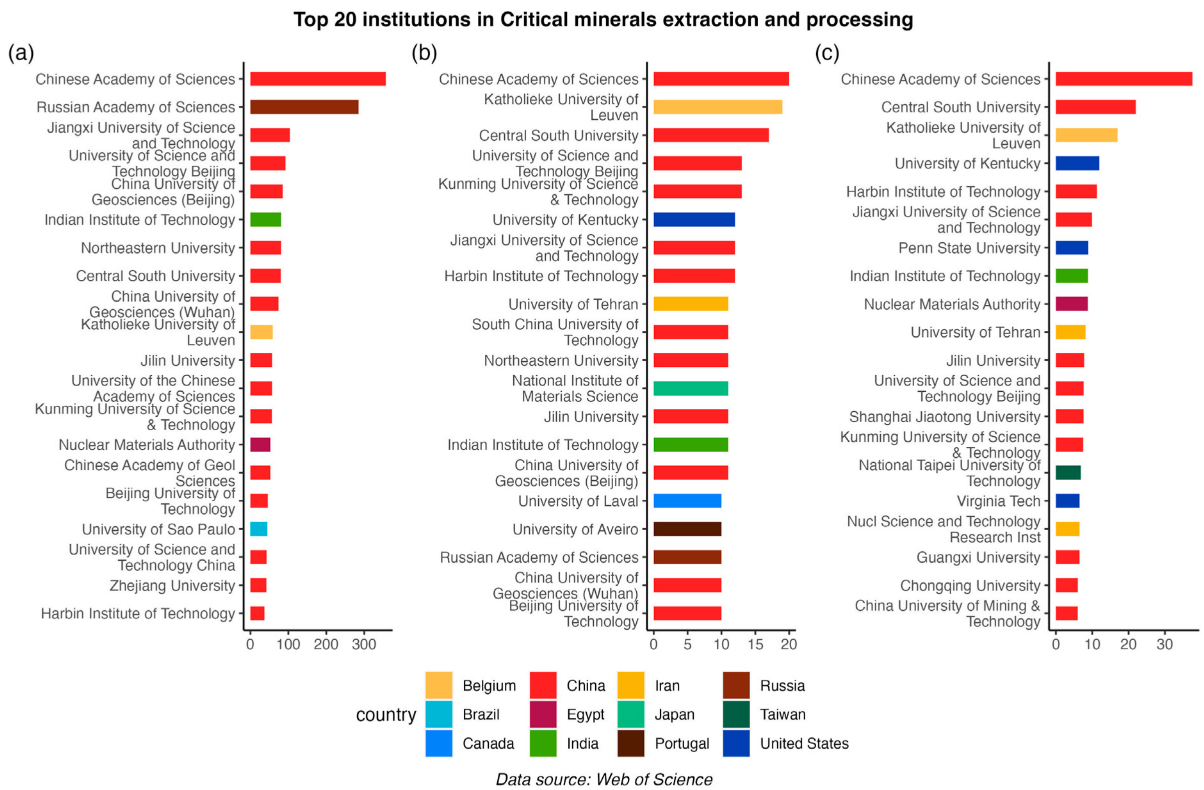
Technology	Top 5 countries					Technology monopoly risk
Nanoscale materials and manufacturing	58.35%	6.73%	4.90%	4.06%	3.84%	10/10 8.67 **high**
Coatings	58.47%	7.34%	5.97%	3.22%	2.84%	8/10 7.96 **high**
Smart materials	42.57%	8.13%	6.96%	6.69%	3.27%	7/10 5.24 **medium**
Advanced composite materials	40.82%	14.03%	7.30%	4.04%	3.93%	8/10 2.91 **medium**
Novel metamaterials	45.56%	16.90%	4.01%	3.89%	3.01%	7/10 2.70 **medium**
High-specification machining processes	36.21%	13.84%	11.75%	3.59%	2.85%	8/10 2.62 **medium**
Advanced explosives and energetic materials	47.10%	21.31%	4.88%	3.96%	3.23%	5/10 2.21 **medium**
Critical minerals extraction and processing	36.68%	13.39%	4.47%	2.79%	2.68%	4/10 2.74 **low**
Advanced magnets and superconductors	33.36%	16.37%	7.54%	7.09%	5.01%	4/10 2.04 **low**
Advanced protection	35.05%	18.72%	5.26%	4.74%	3.04%	6/10 1.87 **low**
Continuous flow chemical synthesis	24.64%	13.90%	5.73%	5.10%	3.85%	4/10 1.77 **low**
Additive manufacturing (incl. 3D printing)	20.41%	20.25%	6.38%	5.27%	4.34%	5/10 1.01 **low**

The largest research publication dataset within the *advanced materials* category is on nanoscale materials, also known as nanomaterials, which have been the subject of half a million publications. Nanoscale materials have various major applications that exploit their engineered mechanical, electrical and photonic properties. The diversity in nanomaterial properties means it's quite difficult to make in-depth assessments about how this critical technology is potentially advancing. Eleven of the 12 subcategories in the *advanced materials* category are directly related to their applications. *Critical minerals extraction and processing* has broader indirect applications in electric batteries, superconductors and magnets.

Notably, reserves of lithium, rare-earth elements and other metals (such as manganese, nickel and cobalt) are considered to be critical minerals as supply-chain issues become important for the manufacture of electric vehicle batteries, which requires a trusted supply of these materials.[177] The risk of lithium shortages is a constant reminder of supply-chain vulnerability.[178] A 2018 report from Austrade proposed a plan for Australia to become a major centre of lithium battery production due to Australia's favourable foreign investment conditions and vast natural resource endowment.[179]

Our *advanced materials* dataset shows that the subcategory of *critical minerals extraction and processing* involves a significant number of China-based institutions, among which the Chinese Academy of Sciences ranks first (see Figure 13), but also shows a diverse number of countries among the top 20 institutions—notably, Belgium's Katholieke University of Leuven ranks second or third in quality metrics.

Figure 13: Top 20 institutions in critical minerals extraction and processing by (a) the weighted number of publications (b) H-index and (c) the weighted number of publications within the top 10% of highly cited publications. Note that some institutions which were equally ranked at 20, were truncated for clarity.



The University of Kentucky is the top ranked US university in *critical minerals extraction and processing*, at the sixth and fourth positions in the H-index and top 10% of highly cited papers, respectively. Iran has two institutions among the top 20 institutions: the University of Tehran (10th in the H-index and ninth in the top 10%), and the Nuclear Science and Technology Research Institute (17th in the top 10% of highly cited papers). Within the quality metrics chart, there are additional institutions focused on nuclear materials: the Nuclear Materials Authority (Egypt) and the National Institute of Materials Science (Japan). Taiwan is also among the top 20 institutions; the National Taipei University of Technology ranks 13th (see Figure 13(c)).

India performs very well in *high-specification machining processes* (Figure 14) and *smart materials* (Figure 15) and is the second ranked country in these technologies in the quality metrics (top 10% of highly cited papers). India's IIT is the top ranked institution in *high-specification machining processes*, and NIT comes close behind ranking third or fourth. India's strong performance is mirrored in its share of global talent training and working in the field, holding an equal standing to China and the US in this respect (Figure 16).

Figure 14: Top 20 institutions in high-specification machining processes by (a) the weighted number of publications (b) H-index and (c) the weighted number of publications within the top 10% of highly cited publications.

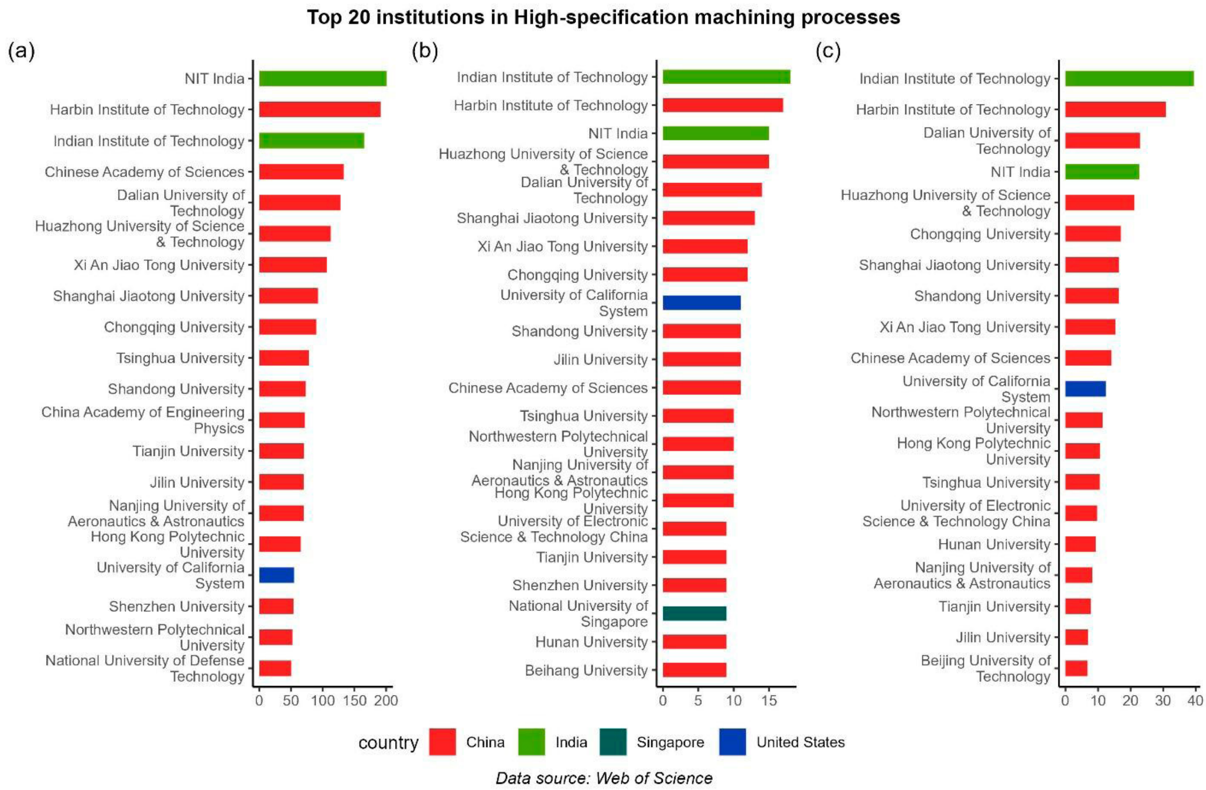


Figure 15: Top 20 institutions in smart materials by (a) the weighted number of publications (b) H-index and (c) the weighted number of publications within the top 10% of highly cited publications.

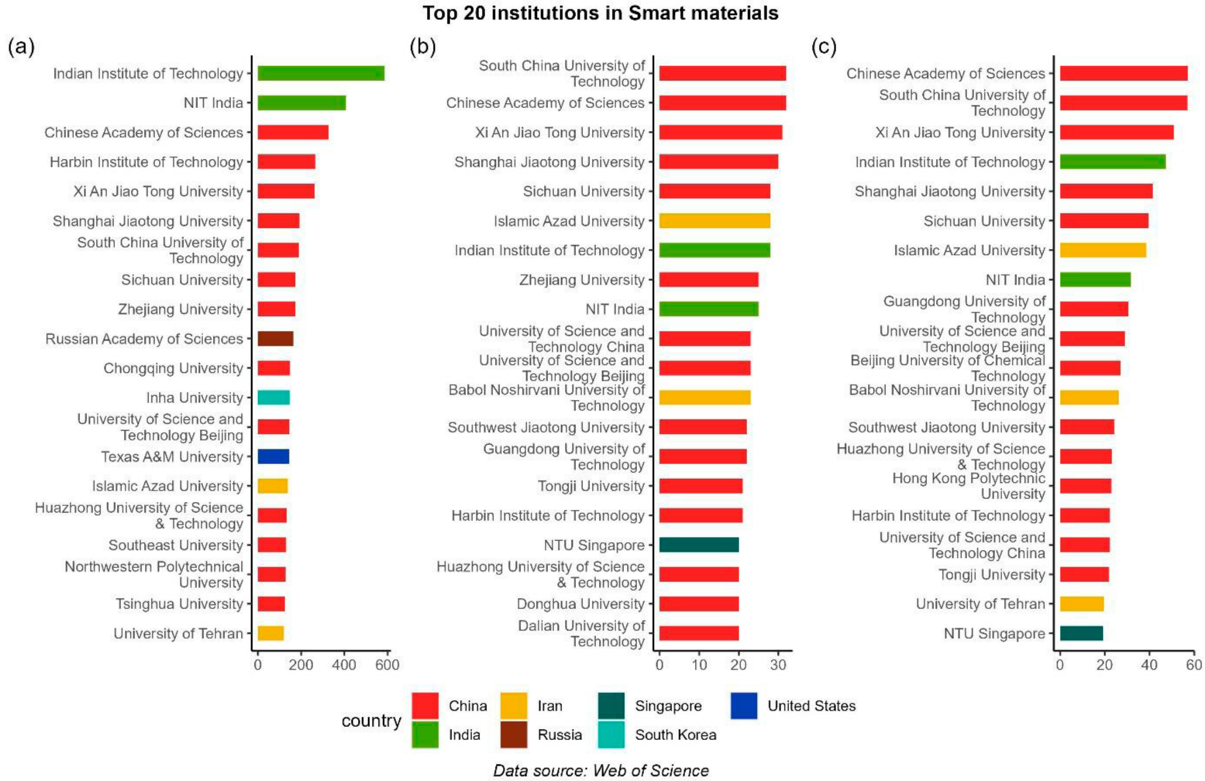
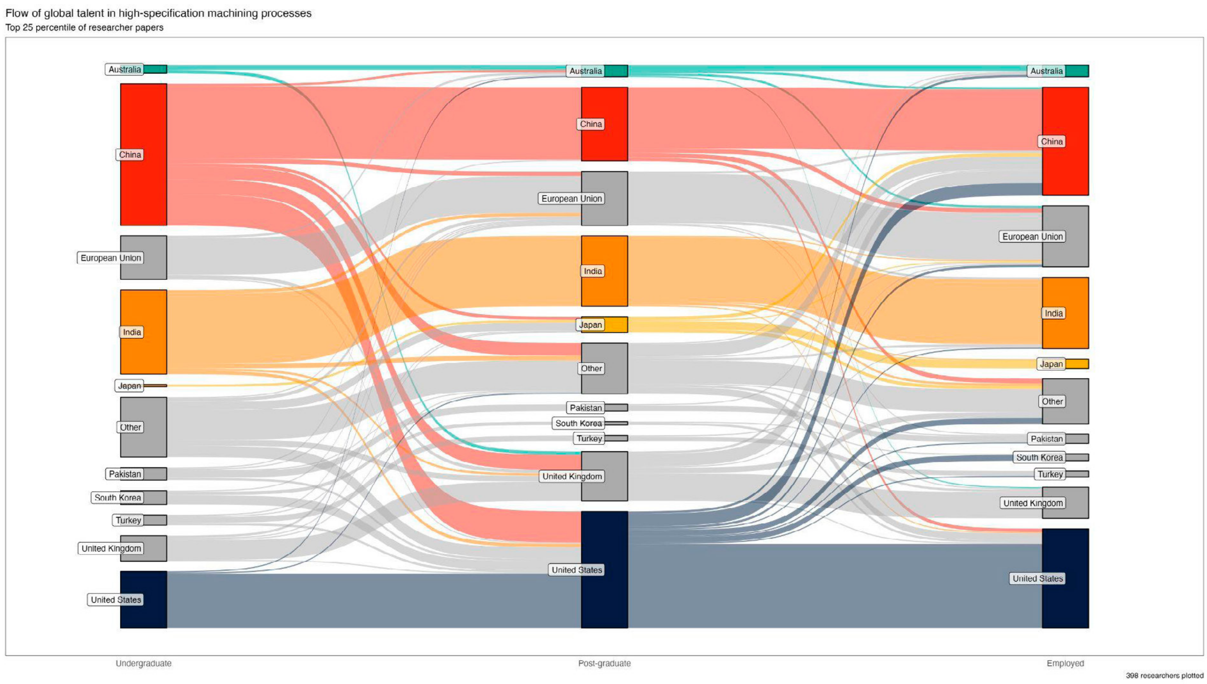
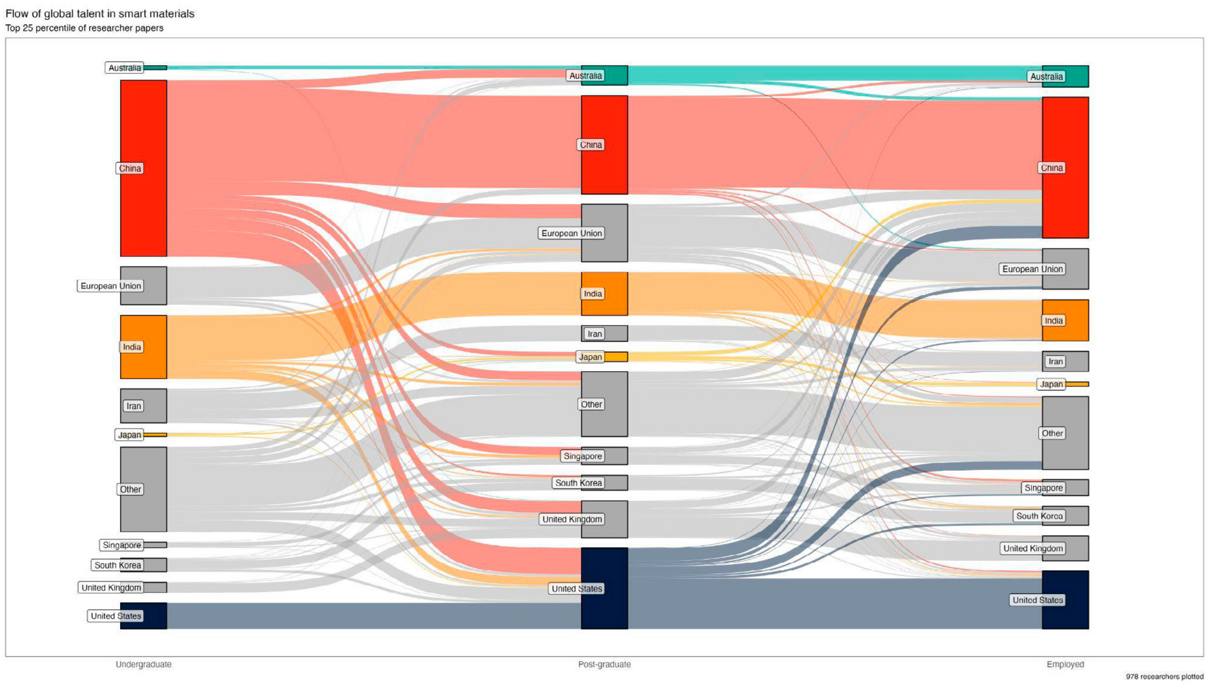


Figure 16: Talent flow of researchers who authored the top 25% of publication in high-specification machining processes.



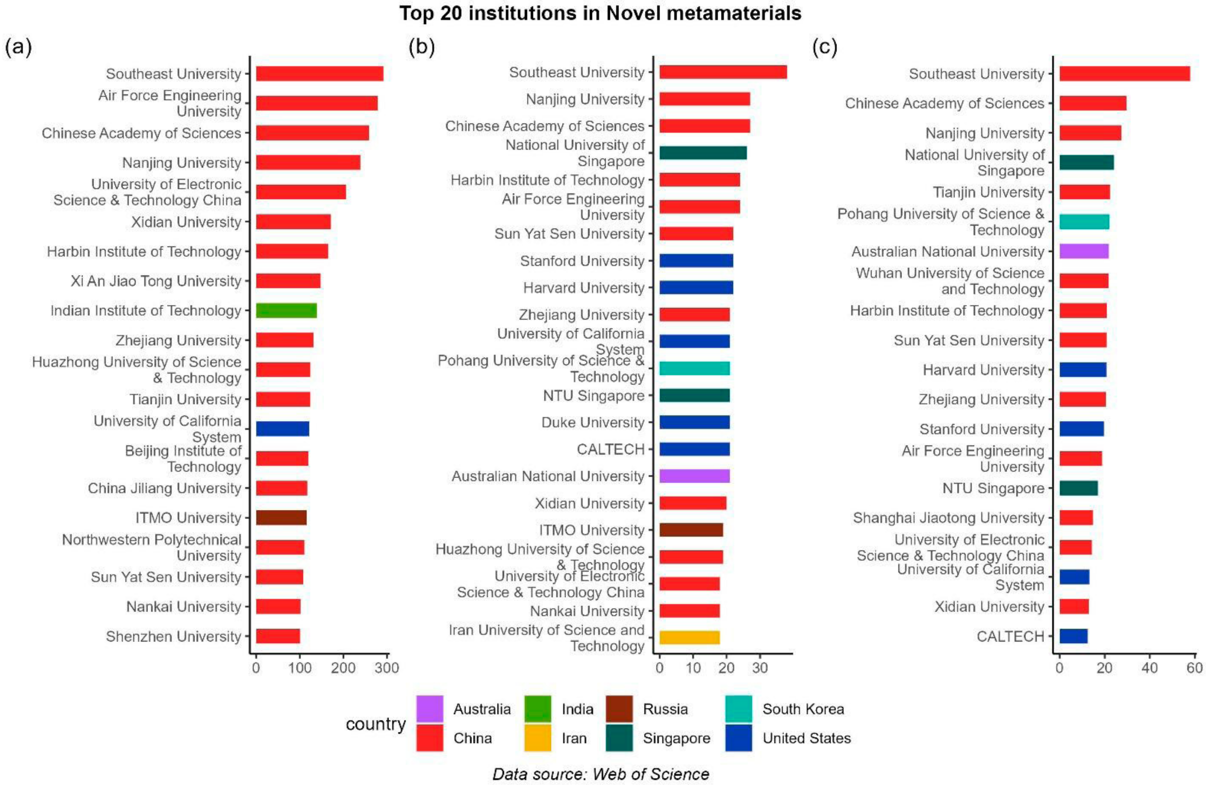
In *smart materials*, three Iranian institutions are ranked among the top 20 institutions: the Islamic Azad University, Babol Noshirvani Institute of Technology and the University of Tehran (Figure 15). NTU Singapore ranks 17th (H-index) and 20th (top 10% of highly cited papers). The supremacy of China in the *nanoscale materials and manufacturing* subcategory is staggering: the Chinese Academy of Sciences and USTC rank first and second, respectively, irrespective of quality metrics, and 19 out of 20 of the top institutions are based in the PRC (for both quality metrics). The only two universities outside of China that crack the top 20 in our dataset are NTU in Singapore (ranked fourth in the H-index) and IIT in India (ranked 20th in the top 10% of highly cited papers). China's dominance in *smart materials* and *nanoscale materials* and *manufacturing* can also be seen in the talent-tracker data as well; China has the single largest country-share of researchers at each of the researcher career stages (Figure 17 for smart materials).

Figure 17: Talent flow of researchers who authored the top 25% of publications in smart materials.



In contrast, the *novel metamaterials* subcategory shows a greater global diversity in terms of institutional performance (Figure 18). Southeast University (China) ranks first, the National University of Singapore ranks second and fourth in the two quality metrics, and the Pohang University of Science and Technology (POSTECH) in South Korea ranks 10th and sixth (Figure 18). The USA has from three to five institutions in the top ranked institutions: Harvard University, Stanford University and the University of California system are among the top 20 institutions. The Australian National University is Australia's first ranked institution in novel metamaterials (10th and seventh in the H-index and top 10% of highly cited articles, respectively).

Figure 18: Top 20 institutions in novel metamaterials by (a) the weighted number of publications (b) H-index and (c) the weighted number of publications within the top 10% of highly cited publications.



Apart from *high-specification machining processes*, there are two subcategories in *advanced materials* in which the PRC doesn't have the top ranked institution: *additive manufacturing* (Figure 19) and *continuous flow chemical synthesis* (Figure 20). For example, in *additive manufacturing*, there are six other countries among the top 20 institutions outside of China and the US: Singapore (NTU, National University of Singapore), Netherlands (Delft University of Technology), the UK (University of Nottingham, University of Manchester), Italy (Politecn Milan, Politecn Torino), Australia (RMIT, University of Queensland) and India (IIT).

Similar diversity can be seen in *continuous flow chemical synthesis* (Figure 20), in which Denmark has one institution (the Technical University of Denmark), Japan has three (the University of Tokyo, Tohoku University and Kyoto University), the UK has three (University College London, the University of Cambridge and the University of Leeds), Germany has two (RWTH Aachen, the Karlsruhe Institute of Technology), and the Netherlands has three (Eindhoven University of Technology, Delft University of Technology and the University of Groningen).

International and national collaborations on these critical technologies can minimise future supply-chain risks and even out the dominance of one country in all critical technologies.

Figure 19: Top 20 institutions in additive manufacturing by (a) the weighted number of publications (b) H-index and (c) the weighted number of publications within the top 10% of highly cited publications.

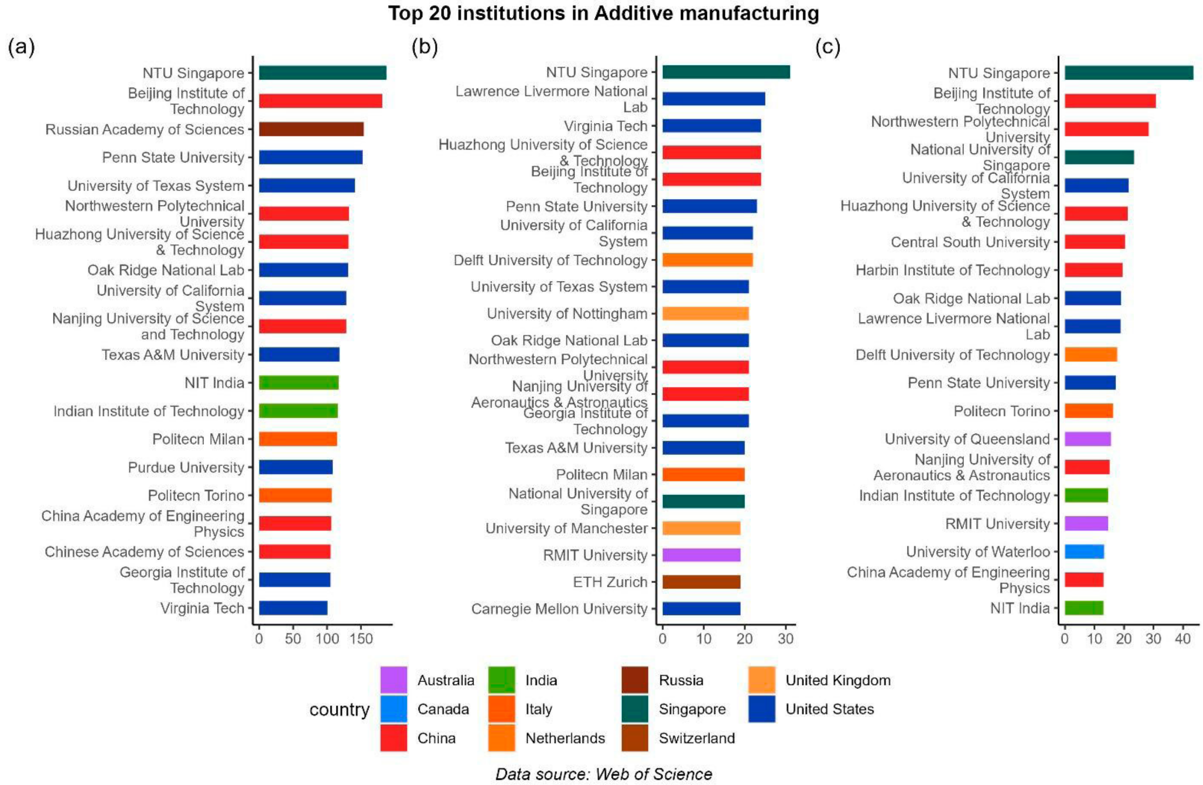
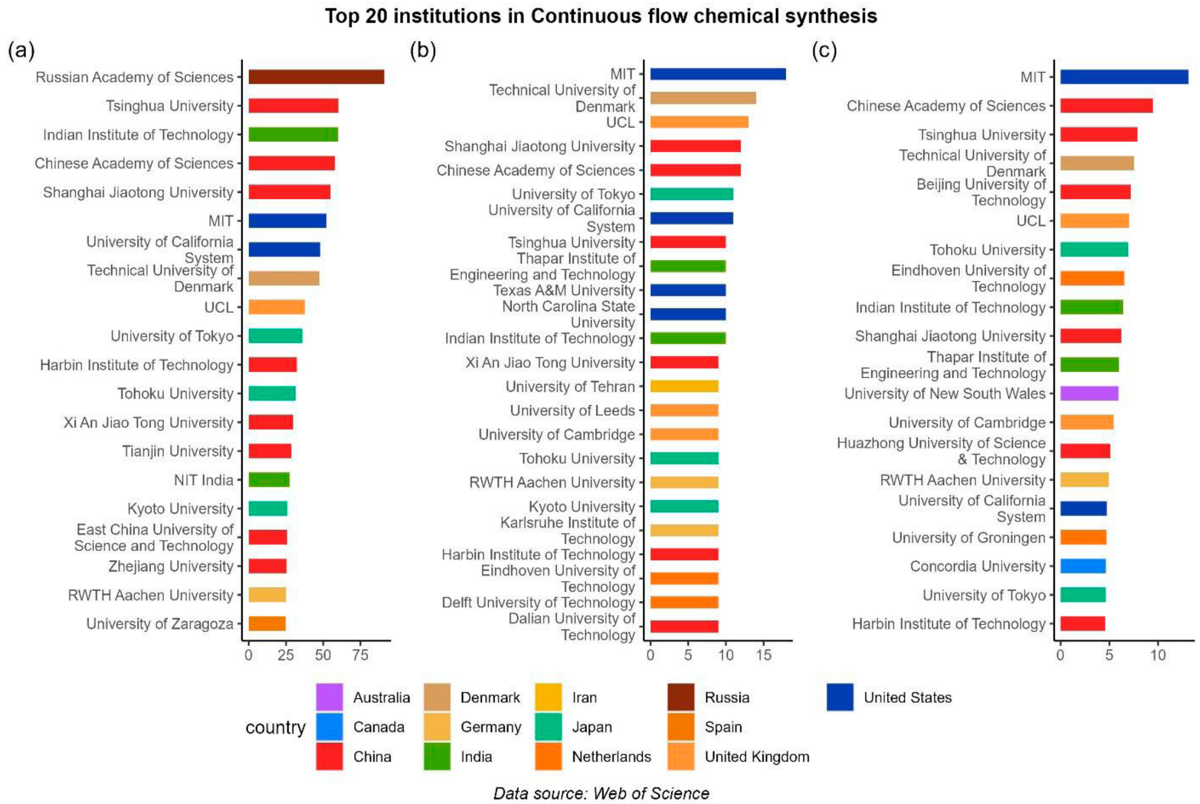


Figure 20: Top 20 institutions in continuous flow chemical synthesis by (a) the weighted number of publications (b) H-index and (c) the weighted number of publications within the top 10% of highly cited publications.



In all the 12 *advanced materials* categories, there are only two institutions that dominate the top 20 institutions by making the list in 11 out of the 12 *advanced materials* subcategories: the Chinese Academy of Sciences and the Harbin Institute of Technology. Notably, the Chinese Academy of Sciences ranks first or second in eight of the 12 subcategories. The IIT makes the top 20 list in 10 out of the 12 categories (with first rank in *high-specification machining processes* and second rank in *advanced composite materials*).

Policy recommendations

Our policy recommendations are grouped into four themes:

1. boosting investment, driving commercialisation and building talent pipelines
2. global partnerships
3. supercharging intelligence efforts
4. moonshots (big ideas).

The four themes contain a total of 23 recommendations. These recommendations seek to advance performance in areas where the current concentration of expertise is likely to result in breakout capability and technology monopoly risk. Ambitions for improved performance in highlighted areas must be balanced with maintaining the edge in leading fields (such as *quantum computing*, *advanced integrated circuits design and fabrication* and *vaccines and medical countermeasures*). We recognise that some governments already have in place some of the following recommendations, but many do not, or only very partially.

It's important to emphasise that research excellence isn't a tap that can be turned on or off at will. Substantial time is needed to establish and develop research excellence to the point where the research is the best in the world, in terms of being highly innovative and genuinely breaking new ground. Similarly, decades of investment can be destroyed by turning off funding in response to short-term pressures. In the language of economics: it isn't a frictionless labour market. Furthermore, we must avoid the trap of rewarding research volume. A notable insight from this work was that many countries, especially Russia, for example, frequently perform well in many technologies according to research volume but drop below the top 20 when evaluated by the H-index or their share of top 10% of publications. High volumes of low-quality research isn't the pathway to success in technology innovation.

(i) Boosting investment, driving commercialisation and building talent pipelines

Assurance of stable long-term funding is important for attracting top talent, and governments must put in place more targeted mechanisms to incentivise universities, research institutes and private industry. There are international talent shortages in all the technologies covered here.[180] As identified in our report, critical technologies often require high-level expertise (postgraduate levels) and/or specialised training. PhD scholarships, and subsequent job opportunities, are currently not adequate to retain our talent onshore. In addition, the lack of a technology ecosystem in some countries is often a driver for skilled researchers and technologists to relocate overseas for improved commercialisation prospects and venture-capital funding. This was the case in Australia, for example, with the 2015 Silicon Valley start-up PsiQuantum.[181] In order to improve their position, countries must focus on building more attractive career pathways in areas such as science, technology, engineering and mathematics (STEM).

1. **Favourable taxation for venture capital investment**

   Venture capital funding drives innovation. Governments should adjust taxation frameworks[182] to encourage private investment flows towards venture capital firms[183] that are supporting technology innovation, R&D and commercialisation.

2. **Proportional investment matching from public funds**

   Resource-rich countries, such as the US, Norway, Canada, Brazil and Australia, should take steps to control 'Dutch disease' during resource booms.[184] 'Dutch disease' diminishes investment in non-booming sectors and so starves venture capital funding for technology innovation when mining investment promises higher returns. One strategy is investment matching whereby private investment is proportionally matched (for example, at 40%) with public funds to stimulate the venture capital market.[185]

3. **Countries need national strategies**

   For individual technologies, governments should develop national strategies that are both clear and ambitious.[186] Commercialisation requires strategic decisions and policies for success. A key example is the story behind TSMC, in which the Taiwanese Government lobbied US semiconductor companies to host its researchers in the 1990s for training in semiconductor processing and headhunted Morris Chang from Intel to come back to Taiwan and set up TSMC.

4. **Public–private partnerships to build commercialisation hubs**

   Governments and the business community should partner to support and build commercialisation hubs, some of which could be placed in research institutions (universities or labs), while others should be built in areas such as science and technology parks. Our data revealed some top performing institutions, which could be paired with well-funded centres of excellence (if not already),[187] creating a critical mass of expert talent and specialised infrastructure to boost cutting-edge research. Universities don't often have the resources to lead critical technologies to commercialisation, but commercialisation expertise in the form of national commercialisation hubs[188] can lead promising technologies to commercialisation and create new technology jobs. New critical technology 'centres of excellence' could be created and equipped with a national commercialisation hub on the same technology to maximise benefits.[189] For example, the positive flow-on effect between Silicon Valley and the University of California system means that researchers feel empowered to approach technology companies with their innovations. Similar dynamics are observed between Eindhoven and Dutch technical universities. We can initiate new technology ecosystems by creating commercialisation pathways and supporting university–industry partnerships. Defence departments should also seek out new partnerships and support commercialisation, the US Defense Advanced Research Projects Agency (DARPA) provides an obvious model to examine closely given its success at fostering innovation and pulling in teams from both academia and private industry.

5. **New technology visas**

   Existing frameworks and minilaterals, including but certainly not limited to the Quad and AUKUS,[190] should be leveraged to establish reciprocal technology visa programs among member countries. Such new visa arrangements should enable easy movement and provide work rights for both early-career and established researchers.[191] For individuals seeking research training, the visa should provide reciprocal recognition of enrolment at the destination university along with a guaranteed period of work rights following successful completion of the training. It's critical that the program supports young researchers to ensure that the best and the brightest are attracted and retained. Visa recipients should be provided with preferential pathways to permanent residency or citizenship at the conclusion of their studies to help reverse the brain drain.[192]

6. **Extra weighting for tech training**

   Governments should create or amend necessary rules or legislation to provide extra weighting for research degrees focused on advancing knowledge of critical technologies to encourage universities to grow (in some countries, funding calculations provide more generous funding for research degrees that fall within a field of study deemed high cost, and these are high-cost fields of study and work).[193]

7. **Critical tech scholarships for both students and technologists**

   Governments should immediately increase funding for specialised PhD scholarships and provide compelling financial incentives for technology companies to run large trainee programs. Each country could tailor such incentives to the technologies they want to specialise in over the coming decades and distribute them via relevant agencies, including education, training and/or science departments. Citizenship eligibility requirements should be considered at the policy design stage, and it may be appropriate for a greater weighting to be given to a country's own citizens to build up greater domestic capability, in addition to those participating in friend-shoring and partnership grant programs (such as in technology visa schemes).

8. **PhD scholarship stipends must be lifted**

   Governments should increase all PhD scholarship stipends to ensure that they're, at the very least, on par with the minimum wage.[194] Doing so would immediately help to revitalise PhD programs and the university sector more broadly. Making this broad-based rather than just focused on critical technology will provide a more substantial boost to university income (via increased enrolment numbers across the board) and support efforts to scale up university-wide infrastructure and services required to deliver high-quality education.

9. **Workforce training and upskilling**

   Countries need to invest in building up their technology ecosystems, and governments should introduce greater workforce training and upskilling initiatives. Such initiatives could include, for example, subsidised training, rebates on specialised courses and support for on-the-job mentoring programs to encourage greater early-career talent flow into particular technology fields of greatest importance to each country.

10. Boost support for policy think tanks

Governments—in addition to the private sector—should fund policy-relevant technology programs within their think-tank communities. Currently, very few think-tanks around the world—especially in the West—have dedicated, high-performing technology programs that can inform and shape policy.

11. Visa screening

Ongoing vigilance is needed in visa screening programs to limit illegal technology transfers (which is often difficult to unearth and trace).[195] This must be particularly strict where visiting personnel are affiliated with defence research organisations associated with non-partner governments[196] and when individuals are involved with foreign technology transfer programs.[197] This shouldn't be a one-time assessment, and governments should be working closely with universities to follow best practice to limit foreign interference proportionately to the national security risk associated with their research programs.[198] Where they don't exist already, governments should build foreign interference committees that include senior government, business and academic representatives to enhance collaboration in countering the various actors that engage in interference and illegal technology transfer in the science and technology fields.

12. Export controls on talent

The strategic application of export controls to place narrow limits on the movements of researchers with expertise in certain critical technology topics must be examined, even if it's considered controversial. The knowledge and skills that expert scientists acquire over a lifetime are extremely valuable and can unlock technology innovation in a range of critical areas. Recruiting personnel to lead research programs in, for example, defence-relevant technologies in adversarial states poses a clear threat to a country's national security (examples relevant to many countries would be one's top researchers leading a cyber, nuclear or defence tech program in Russia, China or Iran). Any restrictions would need to be balanced against an individual's right to freedom of movement, and so those limits should require a serious national-security risk to be clearly identified and be designed to be as minimally invasive as possible. Where such risks arise, entity lists should be used to clearly outline specific countries and research areas to which these limitations apply so that there's no ambiguity. Recent examples include the US's restrictions on its citizens working in Chinese semiconductor companies.[199]

(ii) Global partnerships

13. Build R&D friend-shoring opportunities

Governments should build collective supply-chain resilience by exploring and developing mutually beneficial R&D friend-shoring arrangements.[200] Such arrangements will enable countries to play to their strengths while providing supply guarantees for exposed areas. The arrangements could evolve organically from existing strengths that have emerged from the national research priorities and strategies of the member countries.

14. Divide-and-conquer responsibilities for breadth and depth

Collections of trusted partners (organically or via certain minilaterals) could consider going one step further by entering into a formal agreement that assigns certain countries to take the lead position for a set of related technologies. Those countries could be responsible for establishing or expanding research and commercialisation hubs and hosting guest researchers from member countries. Participation in friend-shoring should be contingent upon signing up to a reciprocal tech talent visa program between members and providing scholarships supporting PhD exchange programs.[201]

15. Partnership grants

Governments should create a special class of research grants to support collaborative critical technology research between countries that sign on to the friend-shoring and visa arrangements described above. Grant eligibility should be contingent on including researchers from several member countries and providing training for young researchers (including 'sandwich' PhDs). This could be modelled on the European Partnerships pillar of the Horizon Europe funding program of the EU.[202] Grants should be aligned with current strengths, national research and manufacturing priorities, or both. Some examples include India, the US and the UK on *high-specification machining processes*; the Quad plus Singapore on *nanoscale materials and manufacturing*; the Quad plus South Korea, Germany and Singapore on *hydrogen and ammonia for power*; the US, Germany, Canada, South Korea and Japan on *space launch systems*; and the Quad and AUKUS plus Italy and Germany on *small satellites*.

(iii) Supercharging intelligence efforts

16. Grip up on critical technology efforts with a strategy

Partners and allies should ensure that their intelligence agencies are 'gripped up' and being led by a whole-of-community strategy. For many, this could require new mechanisms, reporting streams, collection architecture and engagement initiatives. Being led by a clear strategy, in addition to a mission, is crucial, as intelligence communities need to do two things simultaneously: first, support governments as they race to catch up across some or many of these technology fields; second, urgently build greater capability to understand how advanced China's lead really is across a wide range of critical technologies with clear national security, defence, economic and societal implications. Neither is a straightforward task.

17. A new China technology centre

The Five-Eyes partners plus Japan should build a new dedicated China technology collection and analysis centre. This new analytical centre should be built from scratch and involve the creation of new teams and structures, not cobbled together from bits of existing or potential initiatives across countries. All countries involved in this initiative would make significant contributions to rapidly develop new reporting lines on selected China technology topics. That reporting would inform a range of decision-makers and urgently fill any gaps that might currently exist. Such an initiative would be successful only if it's created to pool resources, maximise information sharing and promote innovation in selected critical technology areas. Secondments between countries involved in the initiative would boost trust, sharing and skills transfer and the position of head of this initiative could rotate amongst major contributors. Beyond the initial small group of countries, selected countries could be potentially invited to participate in the centre (such as India and South Korea) once up and running.

Low-hanging fruit: start with open-source intelligence

Multi-government intelligence initiatives are always complicated. Building the initiative to start with open-source efforts offers partners a unique opportunity to move quickly to develop valuable new reporting and analytical streams, including in-depth data-driven analytical contributions. Starting the initiative by building up new multi-government open-source capabilities also offers governments the space and opportunity to deepen collaboration with partners in a more unclassified environment in which lessons learned, tradecraft and innovations (such as research and big-data practices) can be shared before pulling in classified programs of work into the centre.

18. Deepen collaboration between allies and partners

Communities need to maximise intelligence engagement and cooperation in the areas of critical and emerging technologies. Communities must invest more in building and deepening international partnerships; this should include investing in and enhancing 'intelligence diplomacy' capabilities and the sharing of not just information but actual technological and data expertise. Countries can leverage both traditional partnerships (such as the Five-Eyes arrangement and partnerships across Europe) and newer groupings (such as the Quad). In order for democracies to build an aggregate lead and a greater technological edge in the decades to come, intelligence communities will need to play a key role.

19. Collaborate and build partnerships outside of government with research institutes and business

The bulk of technological advancement is occurring outside of government in non-classified spaces, yet some intelligence communities struggle to engage collaboratively outside of their field, let alone outside of government. That needs to change, and communities must ensure that they continue to make an effort to engage influential actors outside of government who can have access to expertise, content and datasets that they don't have access to (some already do such engagement well, but many struggle in this space). One way to deepen such engagement is to boost and better tailor funding support for open-source research, especially in the science and technology fields. Such funding mechanisms already occur in some countries,[203] but sometimes the amounts are too small and grants too restrictive.

20. Intelligence Chiefs must talk and engage publicly more

Finally, intelligence chiefs and other national security seniors must talk more to their publics—and political leaders must allow them that space. The whole point of a public service is to provide frank and fearless advice and analysis to inform better policy- and decision-making. Publics also have a right to also hear frank and fearless advice, and to be informed on the strategic, geopolitical and technological challenges a country, and its region, are facing that will affect society, the economy and their livelihoods.

(iv) Moonshots

Long-term funding via sovereign wealth funds for research, development and tech innovation

21. Establish large sovereign wealth funds

Governments should establish sizeable sovereign wealth funds[204] for research, development and innovation in critical technology that they add to each year. The funds should be set as a percentage of gross national income (such as 0.5%–0.7%), with co-investment from industry. Investment returns should deliver two funding streams: venture-capital funding and scale-up funding. The sovereign wealth funds should support the most promising R&D programs across a broad range of critical technology areas (from climate and energy to AI and quantum), and should be open to both the public and the private sectors.

22. Allocate some of these funds to high-risk, high-reward initiatives

A minimum percentage of funding from the sovereign wealth funds should be allocated to high-risk, high-reward initiatives in selected areas in which the relevant country already has a competitive advantage or is seeking to develop one.[205] The higher risk grants should be administered through a government body (or a committee comprising representatives of multiple relevant agencies) that has visibility of research and innovation occurring in both open-source and classified spaces. It's important that priorities for economic security, intelligence,[206] national security and defence[207] and areas such as climate, energy and environment can be considered and priorities aligned where appropriate.

A Technology Act

23. Governments should look to legislate Technology Acts

Similarly to what was announced in the US's CHIPS Act, partners and allies should explore introducing a major piece of technology legislation that could aim to address many of the policy recommendations outlined above in a cohesive form, especially those recommendations outlined in 'Boosting investment, driving commercialisation and building talent pipelines'. Such an ambitious piece of legislation would involve a whole-of-government approach, in addition to the dedication of influential politicians. In the countries where this hasn't already begun, the findings of this research should help to provide policymakers and political leaders with a rare opening to embark on such ambitious legislation.

Appendix 1.1: Top 5 country visual snapshot

Below is a visual snapshot showing the top 5 countries ranked by their (%) proportion of high-impact research output across 44 technologies. We have added a column (far right), which we've called 'Technology monopoly risk'. This metric seeks to highlight *concentrations of technological expertise in a single country*. It includes:

- number 1 country's share of world's top 10 institutions
- number 1 country's lead over closest competitor (ratio of respective share of top 10% publications)
- a traffic-light rating:
  - high = **8+/10** top institutions in no. 1 country *and* at least **3x times research lead**
  - medium = **5+/10** top institutions in no. 1 country *and* at least **2x times research lead**
  - low = medium criteria not met

Advanced materials and manufacturing

Technology	Top 5 countries					Technology monopoly risk
Nanoscale materials and manufacturing	58.35%	6.73%	4.90%	4.06%	3.84%	10/10 8.67 **high**
Coatings	58.47%	7.34%	5.97%	3.22%	2.84%	8/10 7.96 **high**
Smart materials	42.57%	8.13%	6.96%	6.69%	3.27%	7/10 5.24 **medium**
Advanced composite materials	40.82%	14.03%	7.30%	4.04%	3.93%	8/10 2.91 **medium**
Novel metamaterials	45.56%	16.90%	4.01%	3.89%	3.01%	7/10 2.70 **medium**
High-specification machining processes	36.21%	13.84%	11.75%	3.59%	2.85%	8/10 2.62 **medium**
Advanced explosives and energetic materials	47.10%	21.31%	4.88%	3.96%	3.23%	5/10 2.21 **medium**
Critical minerals extraction and processing	36.68%	13.39%	4.47%	2.79%	2.68%	4/10 2.74 **low**

Advanced magnets and superconductors	33.36%	16.37%	7.54%	7.09%	5.01%	4/10 2.04 **low**
Advanced protection	35.05%	18.72%	5.26%	4.74%	3.04%	6/10 1.87 **low**
Continuous flow chemical synthesis	24.64%	13.90%	5.73%	5.10%	3.85%	4/10 1.77 **low**
Additive manufacturing (incl. 3D printing)	20.41%	20.25%	6.38%	5.27%	4.34%	5/10 1.01 **low**

Artificial intelligence, computing and communications

Technology	Top 5 countries					Technology monopoly risk
Advanced radiofrequency communications (incl. 5G and 6G)	29.65%	9.50%	5.18%	4.89%	4.83%	8/10 3.12 **high**
Advanced optical communications	37.69%	12.76%	5.64%	3.88%	3.48%	8/10 2.95 **medium**
Artificial intelligence (AI) algorithms and hardware accelerators	36.62%	13.26%	4.20%	4.15%	3.48%	7/10 2.76 **medium**
Distributed ledgers	28.38%	11.32%	8.94%	5.54%	4.81%	6/10 2.51 **medium**
Advanced data analytics	31.23%	15.45%	6.02%	4.19%	3.92%	8/10 2.02 **medium**
Machine learning (incl. neural networks and deep learning)	33.20%	17.93%	4.87%	3.87%	3.32%	7/10 1.85 **low**
Protective cybersecurity technologies	23.33%	16.80%	7.67%	5.71%	5.20%	5/10 1.33 **low**
High performance computing	29.31%	25.57%	6.34%	4.68%	3.98%	3/10 1.15 **low**

Advanced integrated circuit design and fabrication	24.18%	21.19%	7.16%	4.46%	3.57%	4/10 1.14 **low**
Natural language processing (incl. speech and text recognition and analysis)	25.73%	23.57%	5.74%	4.55%	3.37%	5/10 1.09 **low**

Energy and environment

Technology	Top 5 countries					Technology monopoly risk
Hydrogen and ammonia for power	60.43%	6.74%	4.71%	2.83%	2.80%	9/10 8.97 **high**
Supercapacitors	64.19%	7.28%	4.89%	4.78%	2.03	10/10 8.81 **high**
Electric batteries	65.44%	11.87%	3.81%	2.80%	2.43%	10/10 5.51 **high**
Photovoltaics	39.33%	9.18%	5.40%	4.90%	3.30%	7/10 4.28 **medium**
Nuclear waste management and recycling	35.95%	16.55%	6.51%	4.51%	4.39%	8/10 2.17 **medium**
Directed energy technologies	39.09%	19.08%	5.88%	5.34%	2.85%	7/10 2.05 **medium**
Biofuels	23.15%	15.48%	5.48%	4.42%	3.65%	5/10 1.50 **low**
Nuclear energy	26.83%	20.45%	6.11%	4.39%	4.26%	4/10 1.31 **low**

Quantum

Technology	Top 5 countries					Technology monopoly risk
Quantum computing	33.90%	15.03%	6.11%	5.52%	4.13%	8/10 2.26 **medium**
Post-quantum cryptography	30.98%	13.30%	6.41%	4.73%	3.69%	4/10 2.30 **low**
Quantum communications (incl. quantum key distribution)	31.47%	16.68%	7.58%	6.45%	3.81%	5/10 1.89 **low**
Quantum sensors	23.70%	23.27%	7.76%	4.29%	4.20%	2/10 1.02 **low**

Biotechnology, gene technology and vaccines

Technology	Top 5 countries					Technology monopoly risk
Synthetic biology	52.42%	16.75%	3.32%	3.07%	2.91%	9/10 3.13 **high**
Biological manufacturing	26.01%	10.35%	9.08%	3.85%	3.17%	6/10 2.51 **medium**
Vaccines and medical countermeasures	28.31%	12.57%	6.18%	6.06%	5.14%	8/10 2.25 **medium**

Sensing, timing and navigation

Technology	Top 5 countries					Technology monopoly risk
Photonic sensors	42.72%	12.52%	5.74%	3.61%	3.06%	8/10 3.41 **high**

Defence, space, robotics and transportation

Technology	Top 5 countries					Technology monopoly risk
Advanced aircraft engines (incl. hypersonics)	 48.49%	 11.69%	 6.96%	 3.93%	 3.60%	7/10 4.15 **medium**
Drones, swarming and collaborative robots	 36.07%	 10.30%	 6.13%	 5.15%	 4.53%	5/10 3.50 **medium**
Small satellites	 24.49%	 17.32%	 7.82%	 4.36%	 4.11%	5/10 1.41 **low**
Autonomous systems operation technology	 26.20%	 21.01%	 5.28%	 5.11%	 3.55%	3/10 1.25 **low**
Advanced robotics	 27.89%	 24.64%	 5.49%	 4.81%	 3.79%	4/10 1.13 **low**
Space launch systems	 19.67%	 18.24%	 9.81%	 8.18%	 6.53%	1/10 1.08 **low**

Appendix 1.2: One-page visual snapshot

Table 6: Lead country and technology monopoly risk.

Technology	Lead country	Technology monopoly risk
Advanced materials and manufacturing		
1. Nanoscale materials and manufacturing	China	high
2. Coatings	China	high
3. Smart materials	China	medium
4. Advanced composite materials	China	medium
5. Novel metamaterials	China	medium
6. High-specification machining processes	China	medium
7. Advanced explosives and energetic materials	China	medium
8. Critical minerals extraction and processing	China	low
9. Advanced magnets and superconductors	China	low
10. Advanced protection	China	low
11. Continuous flow chemical synthesis	China	low
12. Additive manufacturing (incl. 3D printing)	China	low
Artificial intelligence, computing and communications		
13. Advanced radiofrequency communications (incl. 5G and 6G)	China	high
14. Advanced optical communications	China	medium
15. Artificial intelligence (AI) algorithms and hardware accelerators	China	medium
16. Distributed ledgers	China	medium
17. Advanced data analytics	China	medium
18. Machine learning (incl. neural networks and deep learning)	China	low
19. Protective cybersecurity technologies	China	low
20. High performance computing	USA	low
21. Advanced integrated circuit design and fabrication	USA	low
22. Natural language processing (incl. speech and text recognition and analysis)	USA	low
Energy and environment		
23. Hydrogen and ammonia for power	China	high
24. Supercapacitors	China	high
25. Electric batteries	China	high
26. Photovoltaics	China	medium
27. Nuclear waste management and recycling	China	medium
28. Directed energy technologies	China	medium
29. Biofuels	China	low
30. Nuclear energy	China	low
Quantum		
31. Quantum computing	USA	medium
32. Post-quantum cryptography	China	low
33. Quantum communications (incl. quantum key distribution)	China	low
34. Quantum sensors	China	low
Biotechnology, gene technology and vaccines		
35. Synthetic biology	China	high
36. Biological manufacturing	China	medium
37. Vaccines and medical countermeasures	USA	medium
Sensing, timing and navigation		
38. Photonic sensors	China	high
Defence, space, robotics and transportation		
39. Advanced aircraft engines (incl. hypersonics)	China	medium
40. Drones, swarming and collaborative robots	China	medium
41. Small satellites	USA	low
42. Autonomous systems operation technology	China	low
43. Advanced robotics	China	low
44. Space launch systems	USA	low

Appendix 2: Detailed methodology

Data source

Research publication data covering the years 2018 to 2022 was downloaded from the Web of Science (WoS) Core Collection database.[208] Bespoke search queries were developed for each technology area. Each query was designed to capture the bulk of relevant papers while simultaneously excluding irrelevant papers. A concrete example comes from the technology category of *small satellites*. These are often referred to as *micro-satellites*, but that same term also describes a section of DNA with repeating patterns that is important in cancer diagnosis.[209] Best practice techniques for database queries were implemented to handle these edge cases.[210]

Classified research

This project uses publicly available data (via paid subscription), and thus does not capture classified research conducted by defence (and other) departments within governments around the world. Similarly, research conducted by private companies that isn't published publicly is not captured.

Publishing in non-English journals

Since the data used in this report to represent by-country research output was drawn from the WoS Core Collection, the degree to which this database captures the research output of each country is a relevant consideration for the underlying validity of the analysis. This is particularly the case for China, where Xi Jinping has called for scientists to 'publish your best work in your motherland to benefit local society' and has instituted an explicit policy to promote publication in journals based in China.[211] Indeed, China maintains its own bibliometric databases, the largest of which, the Chinese Science and Technology Periodical Citation Database, contains more than 14,000 journals.[212] Research suggests, however, that in the STEM fields research is diffused in both national and international journals, and that those researchers based in China's more prestigious tier-1 universities prefer to publish in international journals. In some fields, such as condensed matter physics, that are relevant to technologies such as photovoltaics and advanced magnets, research suggests that the WoS is wholly capable of capturing publications from China-based researchers.[213]

Although the Chinese policy references support for both English- and Chinese-language journals, as of 2021 around 93% of all China-based journals in STEM fields were in Chinese.[214] For those approximately 500 journals that publish in English, the Chinese Government has committed funds to assist them in attracting submissions from researchers around the world.[215]

We made the decision to include citations only from journals in the WoS Core Collection. As a result, the findings may slightly underestimate the performance of scientists in countries such as China, Japan, Germany and France.[216] While a case can be made for including the Chinese citation database, that would then raise the question: why not also include databases covering journals published in Japan or India? For better or worse, English is the current *lingua franca* of research.

It's also worth noting that because of migration and workforce trends it's likely that some countries are boosted by, for example, talent that they've attracted in from neighbouring countries or regions (especially when they share languages). For example, this is possibly the case for China, which is likely to have strong pockets of talent from Taiwan working at Chinese universities, and for the US, which is likely to have the same from, for example, Canada.

Document types

The bibliographic records used were restricted to journal articles, proceedings papers and data papers.[217] This restricted the dataset to not include bibliographic records that were deemed to not reflect research advances, such as book reviews, retracted publications and letters submitted to academic journals.

Defining high-impact research

There's a large volume of research output,[218] but not all papers are high quality.[219] The incentives for researchers and publishers don't always motivate high-quality research, and researchers in particular are pressured to 'publish or perish.'[220] In their effort to climb league tables,[221] and therefore attract more students,[222] universities push academics to publish in high-impact journals and maximise their citation metrics. Similarly, publishers are vying for their journals to be the avenue of choice for researchers, which helps them sell more subscriptions.[223] We use citation metrics to surface truly innovative or groundbreaking research as summarised briefly below. Specifically, we use the citation count provided by the data column '*times cited, wos core*' rather than '*times cited, all databases*' which includes citations from the WoS Core Collection, Arabic Citation Index, BIOSIS Citation Index, Chinese Science Citation Database, Data Citation Index, Russian Science Citation Index and SciELO Citation Index.[224] Researchers have emphasised the importance of clarifying which citation count is used for analysis.[225] We used citations from the core databases in an effort to minimise the impact of citations from lower quality journals (that is, not included in core collection) to preferentially cite papers from their own nations and artificially elevate articles.[226]

Quality metrics

Weighted citation numbers

Credit for each paper was assigned equally between the authors named on each individual paper.[227] On a five-author paper, each author was attributed 20% credit. If one of those authors listed two separate institutions, each institution would receive 10% credit. The contact address for each author was provided in the data downloaded from Web of Science. A bespoke data-processing pipeline was developed to identify both the country of affiliation and the unique research institution name for each author.

Top 10% highly cited papers

The top tier of high-quality publications on each technology is defined, for this work, as the top 10% most highly cited papers. Publications were partitioned by year in order to control for the observation that papers published earlier have had more time to accumulate citations. The weighted citation calculation was applied to these papers and aggregated at the country level and institution level.

Hirsch index (H-index)

As an alternative quality metric, the Hirsch Index (H-index) was calculated for countries and institutions.[228] While the H-index is best known as a reflection of individual researchers' performance, it has several measurement properties that make it useful. Briefly: the H-index is calculated by ranking a set of publications from highest to lowest cited; you then look down the table to see for how long the citation number is greater than or equal to the row number (see Table 7 below). The last row where this is true is the H-index. One useful measurement property is that a small number of very highly cited papers don't bias the score. Similarly, a large number of papers with few citations don't affect the score. Given that the dataset used is restricted to the 2018–2022 period, countries or institutions that have active research groups in the critical technologies investigated can be compared on an equal basis (that is,
it doesn't favour institutions established decades earlier).

With the H-index, older papers are more likely to have the most citations, so papers that are 3-, 4-, or 5-years-old are most likely to make the cut. In contrast, the top 10% is computed within each year, so the best papers from 2022 get through, as do the best papers of 2021, 2020, 2019 and 2018.

Table 7: H-index example (H-index = 3).

Row number	Citation number	Note
1	1,000	← one paper with extreme citation count only adds 1 to H-index
2	5	
3	3	← H index equal 3 as row number = citation number
...		
100	0	← huge volume of low-citation papers has no impact on H-index

Research lead

The size of the lead held by the first country relative to the second country represents the risk of a technology monopoly developing. If, for example, the first country produces 10 times as much top-quality research as the second country, that increases the likelihood of a breakout capability being discovered and the downstream applications of that technology being controlled by the first country.[229] Where the first and second countries are roughly on par with each other, a stranglehold control of a new technology is less likely to develop. This was calculated as a ratio between the weighted number of papers within the top 10% most highly cited produced by the first ranked and second ranked country (see Appendix 1.1 and 1.2).

Talent tracker

The talent tracker is built by combining two different datasets that answer two distinct questions:

1. Who are the researchers making significant contributions in a particular research area?
2. Which institutions were those researchers educated in?

The first question was addressed through the WoS bibliographic database, following a similar methodology to the research quality metrics (see above), but with a greater emphasis on the individual authors as opposed to the institutions that they're from.

The second question was answered using the ORCID database.[230] This database uses a unique digital identifier (ORCID iD) for each individual researcher in the database that links to their self-uploaded personal information (such as previous employment, education history and so on) and professional information (such as publication history), which tends to be uploaded by the institutions that the researchers are affiliated with. The ORCID iD resolves the author name ambiguity problem, which often complicates the analyses of bibliographic data. This allows, for example, for a Jane Doe conducting vaccine research at the University of Pennsylvania to be distinguished from a Jane Doe in the US Army Corps of Engineers conducting climate hazard research (note that Jane Doe is a fictional example of real scenarios in the data). Researchers are strongly encouraged by their universities or employers to register and maintain their ORCID record.

Conveniently, the WoS bibliographic records include this ORCID iD number alongside each publication for authors who have and choose to list that number. By matching the ORCID iDs listed in the bibliographic data to the career histories listed in the ORCID database, we're able to establish a career history for many of the researchers making contributions to a particular research topic.

The researchers visualised in the talent tracker are those who worked on the top 25 percentile of most highly cited research papers. This percentile threshold was chosen as the lowest common percentile that produced reliable insights across all the technologies. For some technologies, such as machine learning which has around 865,949 authors, the top 25 percentile corresponds to 14,605 complete ORCID career histories (that is, individual talent flow lines in the visualisation). For space-launch systems, with only 2,866 authors, the same 25 percentile threshold corresponds to only 30 ORCID career histories. In interpreting the results, it's therefore important to be mindful of the sample size and how that affects the strength of the data. Additionally, only the first 10 listed authors were extracted from each paper in order to prevent very large collaborations from skewing the data.

The talent tracker has three stages (or levels) for each individual researcher: undergraduate, postgraduate and employed. 'Postgraduate' includes both masters- and doctorate-level qualifications, with preference given to the country where each researcher did their doctorate-level qualification if they have both a masters and a doctorate. 'Employed' corresponds to the country where the institution they are most recently affiliated with is located. The country in which each researcher completed their undergraduate, postgraduate (masters/PhD) training and the country of current employment were used to create talent flows (see Table 8 below) between country nodes.

The height of each node represents the proportion of talent in the specified country at the corresponding stages in their careers. That is, the height of the boxes measures the fraction of global talent in each country by where they completed their undergraduate and postgraduate studies and where they are currently (or most recently) employed.

Since education history data is generally self-uploaded, significant variation existed in how researchers described and identified their educational qualifications. This required some degree of judgement to be exercised in interpreting and standardising those qualifications into one of four categories: 'undergraduate', 'masters' and 'doctorate' degrees, or 'other' in the case that a qualification did not appear to fall into the other categories. This was generally quite straightforward (e.g. 'MSc' as a commonly used abbreviation for Master of Science), but could be difficult at times (e.g. 'diploma'), especially given the plethora of degree-award systems used around the world. Since some terms were also used much more frequently than others, only the 800 or so words and phrases necessary to classify 99% of the education data were considered.

In instances in which a single researcher had two or more education qualifications at the same level (such as two PhDs), then the one most recently completed would be the one considered in the talent tracker. For example, if a researcher was awarded a PhD in Australia in 2014 and a PhD in South Korea in 2018, then the country that that researcher completed their postgraduate studies in, according to the talent tracker, would be South Korea. This was done under the assumption that their most recent PhD would most likely be the one that's relevant to whatever research put them on the talent tracker in the first place.

WoS allows authors to affiliate themselves with multiple institutions for a single research paper, and those institutions are potentially located in different countries. While, for the quality metrics, a fractional weighted count was used to evenly split institutional credit, that wasn't possible for the talent tracker, since it deals with the career histories of individual authors and therefore requires a 1:1 correspondence between each author and the country listed in each node (that is, a single author can't be split between multiple countries at a single level). Unfortunately, this could only be handled, for each WoS author that has listed multiple institutions, by selecting one from that list and ignoring the others. We used the first listed institution.

An important detail to note on interpreting the talent tracker visualisations is that, at the postgraduate level, where there are both inflows and outflows of talent, outflow destinations do not necessarily correlate with inflow sources. That is to say that the researchers leaving a country at the postgraduate level aren't necessarily the same researchers that are entering. For example, consider Figure 21. While it may be reasonable to assume that many of the researchers going to China after completing their postgraduate training in the US are the same researchers that went from China to the US after their undergraduate education, technically the flows would appear the same if, instead, all those researchers stayed in the US for employment, and it was American researchers who were moving to China.

Figure 21: Flow of global talent in advanced optical communications (top 25% of research papers).

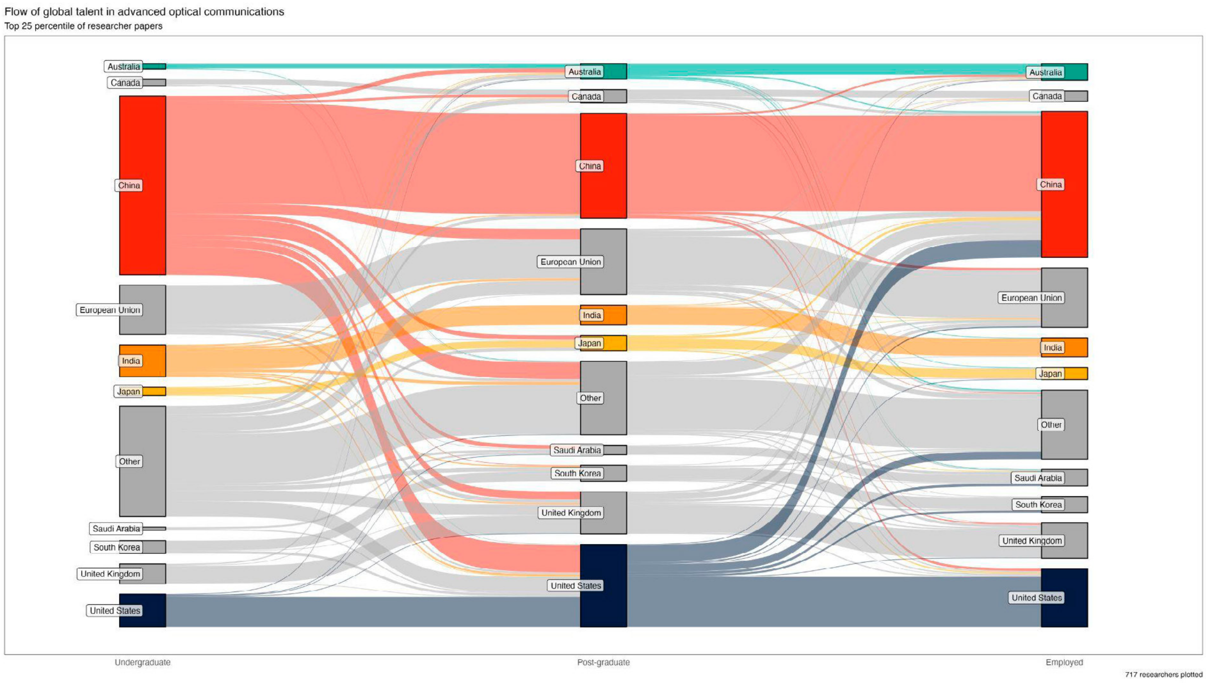


Table 8 below lists the number of data points at three key steps in the talent tracker pipeline for each technology: the number of authors pulled from the top 25 percentile of WoS papers, the number of ORCID iDs listed by those authors, and the number of authors with a complete career history to allow for them to be plotted in the talent tracker visualisations.

Table 8: Number of data points at three key steps in the talent tracker pipeline for each technology.

Technology	Authors	ORCID iDs	Complete career histories
Advanced materials and manufacturing			
1. Nanoscale materials and manufacturing	268,648	61,745	12,475
2. Coatings	11,912	2,129	423
3. Smart materials	22,943	4,856	978
4. Advanced composite materials	26,487	5,546	1,182
5. Novel metamaterials	11,025	2,664	566
6. High-specification machine processes	10,880	2,257	398
7. Advanced explosives and energetic materials	4,778	870	181
8. Critical minerals extraction and processing	13,803	2,540	482
9. Advanced magnets and superconductors	6,319	1,519	280
10. Advanced protection	8,494	1,972	363
11. Continuous -flow chemical synthesis	8,393	2,122	418
12. Additive manufacturing (incl. 3D printing)	18,975	4,248	872
Artificial intelligence, computing and communications			
13. Advanced radiofrequency communications	17,156	4,386	680
14. Advanced optical communications	15,352	3,631	717
15. Artificial intelligence (AI) algorithms and hardware accelerators	2,594	572	116
16. Distributed ledgers	15,433	3,632	593
17. Advanced data analytics	27,836	6,339	1,117
18. Machine learning (incl. neural networks and deep learning)	349,189	85,432	14,605
19. Protective cybersecurity technologies	17,198	4,201	674
20. High performance computing	14,684	3,348	704
21. Advanced integrated circuit design and fabrication	8,177	1,929	332
22. Natural language processing (incl. speech recognition and analysis)	32,701	6,697	1,112
Energy and environment			
23. Hydrogen and ammonia for power	40,760	9,315	2,069
24. Supercapacitors	26,708	5,239	1,195
25. Electric batteries	53,966	11,524	2,569
26. Photovoltaics	76,461	18,983	3,850
27. Nuclear waste management and recycling	9,448	1,881	374
28. Directed energy technologies	11,700	2,787	481
29. Biofuels	40,170	8,794	1,752
30. Nuclear energy	21,059	4,139	783

Quantum			
31. Quantum computing	15,323	4,266	845
32. Post-quantum cryptography	3,356	740	115
33. Quantum communications (incl. quantum key distribution)	5,630	1,523	319
34. Quantum sensing	20,934	5,303	1,058
Biotechnology, gene technology and vaccines			
35. Synthetic biology	28,447	6,313	1,439
36. Biological manufacturing	59,907	13,493	2,610
37. Vaccines and medical countermeasures	82,761	15,258	2,678
Sensing, timing and navigation			
38. Photonic sensors	102,022	23,938	4,551
Defence, space, robotics, transportation			
39. Advanced aircraft engines (incl. hypersonics)	2,406	481	85
40. Drones, swarming and collaborative robots	8,574	2,082	332
41. Small satellites	6,398	1,382	252
42. Autonomous systems operation technology	35,184	9,050	1,508
43. Advanced robotics	44,835	10,088	1,778
44. Space launch systems	1,003	208	30

Data-processing pipelines

Data-processing pipelines were developed to identify the country and research institution in which each individual researcher works, as well as to place awarded degrees into standardised categories. This involved text processing and pattern matching to achieve high rates of entity resolution. This work was performed iteratively over a period of months to handle the myriad ways in which a research institution or degree level can be described. The pipeline processes cases in which just the name of the university is provided, or in which both the lab name and university name are given. Of course, we had to also account for common abbreviations as well as misspellings. There were also situations in which unrelated institutions in different countries had the same abbreviations. Similarly, global technology companies were listed with the country where the research was carried out in order to capture the geopolitical aspect of the technology. This processing was conducted for 12.7 million author names listed in the 2.2 million research papers covered by this report.

Visualisation

Graphs of the top 20 institutions show more than 20 when a tie occurs. For example, if the institutions ranked 19th, 20th, and 21st have the same score, the chart automatically shows 21 institutions. Likewise for the talent tracker visualisations, more than 10 distinct entities are shown if there is a 10th place tie in the sum of national talent across the undergraduate, postgraduate and employment levels.

Entity resolution

The collection of bibliometric data is fraught with challenges in grouping publications from the same affiliations or institutions in the same group. Notably, there some are enormous institutions; for example, the Chinese Academy of Sciences has 116 institutes in various parts of China, which were grouped together. The Indian Institutes of Technology (IITs), with 23 different institutions, was grouped. Similarly, institutions of the Russian Academy of Sciences were grouped together, as were institutions of the Austrian Academy of Sciences. In addition, some universities in the US were grouped as a system; for example, the University of California includes the 10 University of California campuses, including the University of Santa Barbara, University of California Berkeley and University of California Los Angeles. Within the institutions, tech companies such as Google, Microsoft, Intel and Samsung are visible, and the country is generally specified in order to differentiate between different locations. The European Space Agency was separated according to country affiliation but could have generated a larger count with all European countries and allies counted together.

The US Department of Energy (US DoE) has national laboratories affiliated with it, such as the Ames National Laboratory, the Lawrence Berkeley National Laboratory and the Los Alamos National Laboratory. The individual US national labs are kept separate in this report. Another challenge arose from papers using, for example, 'Centre of Excellence for Additive Manufacturing' instead of the affiliation or grouping. Similarly named affiliations such as 'Harvard–MIT Center for Ultracold Atoms' and 'MIT–Harvard Center for Ultracold Atoms' were group together. Well over 200 regex (regular expression) matches for institutions were used to accurately group publications from the same institution together.

For global tech companies, the companies were listed with their host country, differentiating between IBM (US) and IBM (Switzerland).

Technology definitions and stakeholder engagement

Technology definitions were based on the Australian Government critical technology list published August 2022 (with the odd minor deviation).[231] We consulted with multiple governments (and often multiple departments and agencies within a government) and with other stakeholders on other lists and also on which technologies to focus on first. Much of this engagement also helped to feed into and inform different parts of this project. We thank those stakeholders for those very useful discussions. ASPI aims to continue to build, and improve, this program of work over the coming years, and that will involve adding more technologies to the *Critical Technology Tracker*, and possibly more features.

Appendix 3: Database search hits

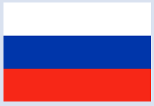
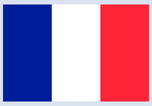
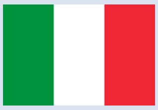
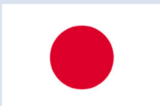
Table 9: Database search hits and number of top 10% highly cited papers.

Technology	Database hits	Top 10%[a]
Advanced materials and manufacturing		
1. Nanoscale materials and manufacturing	477,198	51,830
2. Coatings	10,612	1,209
3. Smart materials	30,782	3,309
4. Advanced composite materials	27,564	2,879
5. Novel metamaterials	14,533	1,580
6. High-specification machining processes	11,266	1,309
7. Advanced explosives and energetic materials	5,659	694
8. Critical minerals extraction and processing	10,949	1,183
9. Advanced magnets and superconductors	6,241	706
10. Advanced protection	8,836	930
11. Continuous flow chemical synthesis	7,095	770
12. Additive manufacturing (incl. 3D printing)	22,583	2,353
Artificial intelligence, computing and communications		
13. Advanced radiofrequency communications (incl. 5G and 6G)	40,803	4,273
14. Advanced optical communications	17,881	1,952
15. Artificial intelligence (AI) algorithms and hardware accelerators	2,172	229
16. Distributed ledgers	23,140	2,467
17. Advanced data analytics	28,444	2,976
18. Machine learning (incl. neural networks and deep learning)	526,738	56,602
19. Protective cyber security technologies	23,610	2,557
20. High performance computing	13,313	1,424
21. Advanced integrated circuit design and fabrication	7,016	779
22. Natural language processing (incl. speech and text recognition and analysis)	40,987	4,539
Energy and environment		
23. Hydrogen and ammonia for power	56,248	5,945
24. Supercapacitors	35,114	3,704
25. Electric batteries	88,362	9,270
26. Photovoltaics	118,248	12,526
27. Nuclear waste management and recycling	8,668	1,032
28. Directed energy technologies	12,713	1,378
29. Biofuels	51,457	5,457
30. Nuclear energy	19,412	2,257
Quantum		
31. Quantum computing	18,732	1,932
32. Post-quantum cryptography	4,146	462
33. Quantum communications (incl. quantum key distribution)	6,173	679
34. Quantum sensors	16,691	1,771

Biotechnology, gene technology and vaccines		
35. Synthetic biology	27,389	2,889
36. Biological manufacturing	127,852	13,471
37. Vaccines and medical countermeasures	65,856	7,204
Sensing, timing and navigation		
38. Photonic sensors	110,122	12,342
Transportation, robotics and space		
39. Advanced aircraft engines (incl. hypersonics)	3,275	356
40. Drones, swarming and collaborative robots	9,307	1,052
41. Small satellites	5,563	605
42. Autonomous systems operation technology	42,418	4,412
43. Advanced robotics	51,748	5,313
44. Space launch systems	871	95
Total	**2,237,787**	**240,702**

a Not exactly 1/10th due to papers with the same number of citations at 0.9 quantile cut point

Appendix 4: Flags

Country	Flag	Country	Flag
Australia		South Korea	
Canada		Malaysia	
China		Netherlands	
Germany		Russia	
France		Saudi Arabia	
India		Singapore	
Iran		United Kingdom	
Italy		United States	
Japan			

Notes

1 Visit the *Critical Technology Tracker* site for a list and explanation of these 44 technologies: techtracker.aspi.org.au/list-of-technologies.

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3 See 'China's science and technology vision' on page 14.

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Acronyms and abbreviations

AI	artificial intelligence
AUKUS	a trilateral security pact between Australia, the United Kingdom, and the United States
CCP	Chinese Communist Party
EU	European Union
GDP	gross domestic product
IIT	Indian Institute of Technology
IMEC	Interuniversity Microelectronics Centre (Belgium)
MIT	Massachusetts Institute of Technology
NTU	Nanyang Technological University
ORCID	Open Researcher and Contributor ID
PRC	People’s Republic of China
Quad	Quadrilateral Security Dialogue
R&D	research and development
SIA	Semiconductor Industry Association
SQuID	superconducting quantum interference device
STEM	science, technology, engineering and mathematics
TSMC	Taiwan Semiconductor Manufacturing Corporation
UC	University of California
US DoE	UD Department of Energy
USTC	University of Science and Technology (China)
WoS	Web of Science

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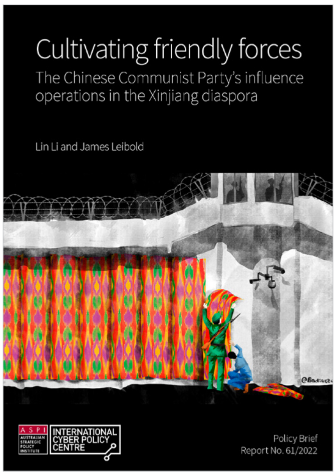

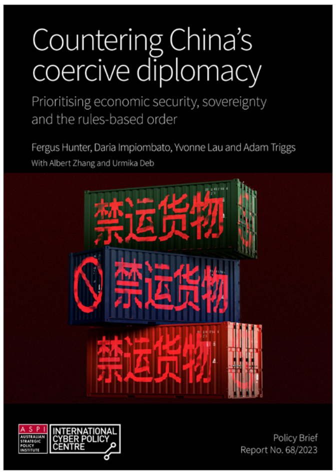

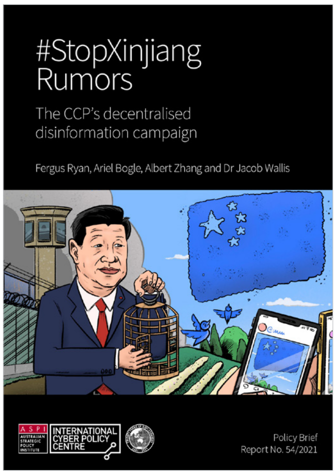

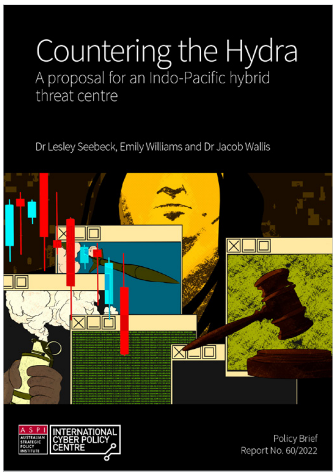

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