*Shows newly added technologies and new data

ADVANCED SENSORS / BIOTECHNOLOGIES: Top 10 country snapshot

Below is a snapshot showing data from ASPI's *Critical Technology Tracker* (techtracker.aspi.org.au/). It sets out the top 10 countries, ranked by their (%) proportion of high-impact research output, across 34 critical technologies. For example:

Technology	Technology monopoly risk	Lead institution	Top 10 countries									
Genetic engineering*	8/10 1.61 low	University of California System	 41.3%	 25.6%	 4.6%	 4.3%	 2.4%	 2.1%	 2.0%	 1.9%	 1.6%	 1.5%

ASPI's Critical Technology Tracker:
The Critical Technology Tracker focuses on a key performance measure of scientific and technological capability—high-impact research—and reveals where countries, universities, national labs and companies around the world have a competitive advantage in this measure across (now) 64 technologies. Another feature of the Critical Technology Tracker is a 'talent tracker' which reveals the flow of global talent in these technologies and highlights brain gains and brain drains for each country. To measure 'high-impact research' we collected and analysed the top 10% of the most highly cited papers (2.4 million papers published 2018-2022) to generate insights into which countries and organisations are publishing the greatest share of high-quality and innovative research in critical technology and defence fields.

New Findings:
In this update, we add seven new technologies to the broad category of Advanced Sensors (atomic clocks, gravitational-force sensors, inertial navigation systems, magnetic field sensors, multispectral and hyperspectral imaging sensors, satellite positioning and navigation, radar), four additional technologies to the broad category of Biotechnologies (novel antibiotics and antivirals, genetic engineering, genome and genetic sequencing, nuclear medicine and radiotherapy), one new technology to AI, Computing and Communication (mesh and ad hoc networks) and one new technology to Advanced Materials and Manufacturing (wide-bandgap and ultra-wide-bandgap technologies). Quantum sensors and photonic sensors were included in the first release of the Critical Technology Tracker. In this release, we have reviewed and updated our dataset for photonic sensors to ensure it is inclusive of all relevant sub-categories and technologies. We include sonar and acoustic sensors, photonic sensors and quantum sensors in this category comparison. Similarly, we compare all the biotechnologies in this update.

The Advanced Sensor technologies encompass devices with extremely sensitive detection capabilities for magnetic and gravitational fields, light and radio waves, as well as measuring time with incredible precision. Of the 10 advanced sensor technologies, four have a high technology monopoly risk, three have a medium risk and the remaining three are low risk. In the advanced sensors category, NIST is the only US institution to be the top ranked institution in our quality metrics, the Chinese Academy of Sciences is the top institution in four technologies, Wuhan University in three technologies, Beihang University and Harbin Engineering University in one technology. The Chinese Academy of Sciences' publications are predominantly in optics for the photonic sensors and radar technologies, and geosciences for gravitational field sensors. Wuhan University's publications are predominantly in the remote sensing field especially in multispectral/hyperspectral imaging sensor and satellite positioning and navigation technologies. In multispectral/hyperspectral imaging (high technology monopoly risk), the Mississippi State University and University of California are the only US institutions in the top 20 in our quality metrics. The University of Extremadura in Spain features in the top 20 institutions for the two quality metrics used. Germany features strongly in the H-index chart with the German Aerospace Center (7th) and the Technical University of Munich (8th) and Helmholtz Zentrum Dresden Rossendorf. Our analysis shows that China's significant lead in the quality metrics in advanced sensors is an indication of significant research investments in these technologies. Four of these technologies have a high technology monopoly risk and can translate to future technological dominance.

The Critical Technology Tracker focus on seven biotechnologies, namely, biological manufacturing, genetic engineering, genome and genetic sequencing and analysis, novel antibiotics and antivirals, nuclear medicine and radiotherapy, synthetic biology, vaccines and medical countermeasures. China leads in four of the seven technologies with synthetic biology having a high tech monopoly risk rating. The Chinese Academy of Sciences is the top ranked institution in novel antibiotics and antivirals, and synthetic biology. The US leads in three biotechnologies with the University of California system as the top ranked institution in three techs, genetic engineering, genome and genetic sequencing analysis and vaccines and medical countermeasures and the University of Texas system ranked first in nuclear medicine and radiotherapy. India has the top ranked institution, the Indian Institute of Technology in biological manufacturing. The technology leads are more equally partitioned between China (leading in four techs) and the United States (leading in three techs) in biotechnologies compared to the other broad tech category.

Potential future technological capability:

What ASPI's Critical Technology Tracker provides – beyond datasets indicating research performance – are its unique insights into strategy, intent and potential future capabilities. It also demonstrates the spread and concentration of global expertise across a range of critical areas. In some cases, countries are leading because they are well ahead across the entire technology development process including research, commercialisation, manufacturing and supply (for example China's stunning lead in electric batteries). In other cases, a country may be leading in high impact research output because it (and its institutions such as universities, national labs and companies) is seeking to catch-up through significant investment, typically incentivised by government funding and policy directives.

ADVANCED SENSORS / BIOTECHNOLOGIES: Top 10 country snapshot

Why high-impact research is important:
Scientific and technological innovation is typically underpinned by high impact research. There are clear links between 1) high-impact research, 2) scientific and technological breakthroughs, and 3) commercialisation. Our report discusses this in depth at: www.aspi.org.au/report/critical-technology-tracker. Whether the focus is hyper-sonics or autonomous underwater vehicles, actualising research performance into major technological gains can be a difficult step requiring other inputs, such as public and private investment, an effective manufacturing sector and the right policy and regulatory frameworks.

The technology monopoly risk traffic light

This metric highlights *concentrations of technological expertise in a single country*. It incorporates two factors: 1) how far ahead the leading country is relative to the next closest competitor, and 2) how many of the world's top 10 institutions that produce high-impact research are located in the leading country. Naturally, these are related, as leading institutions are required to produce high-impact research. This metric, based on high-impact *research output*, is intended as a leading indicator for potential future dominance in technology 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 2.5 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.
The two metrics along with the traffic light are given in the column on the left hand side of the *top 10 country rankings* tables.

Advanced Sensor Technologies

Technology	Technology monopoly risk	Lead institution	Top 10 countries									
Atomic clocks*	7/10 2.01 medium	NIST (United States)	36.0%	17.9%	12.7%	5.3%	4.6%	3.2%	2.9%	2.3%	2.0%	1.9%
Gravitational-force sensors*	3/10 1.27 low	Chinese Academy of Sciences	20.5%	16.1%	9.3%	7.0%	6.2%	5.6%	2.8%	2.7%	2.6%	1.7%
Inertial navigation systems*	9/10 3.52 high	Wuhan University	44.0%	12.5%	4.2%	4.1%	4.1%	3.7%	2.9%	2.4%	2.4%	2.1%
Magnetic field sensors*	3/10 1.65 low	Beihang University	28.4%	17.2%	8.8%	8.4%	3.7%	2.8%	2.5%	2.3%	1.8%	1.8%
Multispectral and hyperspectral imaging sensors*	9/10 4.29 high	Wuhan University	48.9%	11.4%	4.4%	3.6%	3.3%	2.7%	2.3%	2.2%	2.2%	1.4%
Photonic sensors[1]	8/10 3.53 high	Chinese Academy of Sciences	43.7%	12.4%	5.1%	3.9%	3.1%	3.0%	2.3%	1.8%	1.7%	1.7%
Quantum sensors	5/10 1.02 low	Chinese Academy of Sciences	23.7%	23.3%	7.8%	4.3%	4.3%	3.9%	2.7%	2.7%	2.6%	2.5%
Radar*	7/10 2.54 medium	Chinese Academy of Sciences	40.0%	15.7%	5.1%	4.7%	4.6%	3.3%	2.5%	2.4%	1.9%	1.6%

[1] In this release, we have reviewed and updated our dataset for photonic sensors to ensure comprehensive coverage of the technology field.

Satellite positioning and navigation*	6/10 2.56 medium	Wuhan University	36.3%	14.2%	5.4%	4.2%	3.7%	2.7%	2.6%	2.6%	2.5%	2.4%
Sonar and acoustic sensors	9/10 3.96 high	Harbin Engineering University (China)	49.6%	12.5%	6.3%	3.9%	2.9%	2.8%	2.5%	1.6%	1.6%	1.5%

Biotechnologies

Technology	Technology monopoly risk	Lead institution	Top 10 countries									
Biological manufacturing	6/10 2.49 medium	Indian Institute of Technology	26.0%	10.4%	9.1%	3.8%	3.3%	3.2%	3.0%	2.9%	2.7%	2.4%
Genetic engineering*	8/10 1.61 low	University of California System	41.3%	25.6%	4.6%	4.3%	2.4%	2.1%	2.0%	1.9%	1.6%	1.5%
Genome and genetic sequencing and analysis*	6/10 1.21 low	University of California System	31.3%	25.8%	4.7%	4.2%	2.6%	2.4%	2.3%	2.2%	2.2%	2.0%
Novel antibiotics and antivirals*	4/10 1.95 low	Chinese Academy of Sciences	27.8%	14.3%	10.7%	5.3%	3.6%	2.9%	2.6%	2.4%	2.4%	2.2%
Nuclear medicine and radiotherapy*	5/10 1.42 low	University of Texas system	29.0%	20.3%	6.2%	5.4%	5.1%	4.4%	3.4%	3.3%	3.0%	2.2%
Synthetic biology	9/10 3.12 high	Chinese Academy of Sciences	52.4%	16.8%	3.3%	3.1%	2.9%	2.7%	1.8%	1.6%	1.3%	1.1%
Vaccines and medical countermeasures	8/10 2.26 medium	University of California System	28.3%	12.6%	6.2%	6.2%	5.1%	4.2%	2.7%	2.4%	2.3%	2.2%

*Shows newly added technologies and new data

Advanced Information and Communication Technologies

Technology	Technology monopoly risk	Lead institution	Top 10 countries									
Advanced undersea wireless communication	8/10 4.03 high	King Abdullah University of Science & Technology (S.A.)	44.6%	11.1%	7.1%	6.5%	3.9%	3.0%	2.6%	2.4%	2.3%	1.5%
Advanced optical communications	8/10 2.95 medium	Chinese Academy of Sciences	37.7%	12.8%	5.6%	3.9%	3.5%	2.8%	2.7%	2.5%	2.5%	2.2%
Advanced radiofrequency communications	8/10 3.17 high	Xidian University	29.9%	9.4%	5.4%	5.0%	4.8%	4.7%	2.8%	2.7%	2.6%	2.5%
Mesh networks/infrastructure independent communication technologies*	6/10 2.01 medium	NIT India	29.0%	14.4%	8.6%	4.3%	3.4%	3.0%	3.0%	2.6%	2.6%	2.4%

Advanced Materials and Manufacturing

Technology	Technology monopoly risk	Lead institution	Top 10 countries									
Additive manufacturing	5/10 1.01 low	NTU Singapore	20.4%	20.2%	6.7%	5.3%	4.3%	4.1%	4.1%	4.0%	2.7%	2.1%
Advanced composite materials	8/10 2.92 medium	Chinese Academy of Sciences	40.8%	14.0%	7.3%	4.0%	3.9%	2.1%	2.0%	2.0%	1.9%	1.6%
Advanced explosives and energetic materials	5/10 2.21 medium	Nanjing University of Science and Technology	47.1%	21.3%	4.9%	4.0%	3.2%	3.0%	1.9%	1.4%	1.3%	1.3%

*Shows newly added technologies and new data

Advanced magnets and superconductors	4/10 2.04 low	Chinese Academy of Sciences	33.4%	16.4%	7.5%	7.1%	5.0%	4.4%	4.1%	2.4%	2.3%	1.7%
Advanced protection	6/10 1.87 low	Dalian Maritime University	35.1%	18.7%	5.3%	4.7%	3.0%	2.7%	2.6%	2.6%	2.1%	2.1%
Coatings	9/10 7.96 high	Chinese Academy of Sciences	58.5%	7.3%	6.0%	3.2%	2.8%	1.8%	1.8%	1.6%	1.5%	1.3%
Continuous flow chemical synthesis	4/10 1.77 low	MIT	24.6%	13.9%	5.7%	5.1%	3.8%	3.8%	3.7%	3.6%	3.1%	3.0%
High-specification machining processes	8/10 2.62 medium	Indian Institute of Technology	36.2%	13.8%	11.8%	3.6%	2.9%	2.3%	2.0%	1.7%	1.6%	1.6%
Critical minerals extraction and processing	4/10 2.74 low	Chinese Academy of Sciences	36.7%	13.4%	4.5%	2.8%	2.7%	2.4%	2.4%	2.3%	2.2%	2.1%
Nanoscale materials and manufacturing	10/10 8.67 high	Chinese Academy of Sciences	58.3%	6.7%	4.9%	4.1%	3.8%	1.9%	1.5%	1.3%	1.3%	1.2%
Novel metamaterials	7/10 2.70 medium	Southeast University (China)	45.6%	16.9%	4.0%	3.9%	3.0%	3.0%	2.7%	2.2%	2.1%	2.0%
Smart materials	7/10 5.24 medium	Chinese Academy of Sciences	42.6%	8.1%	7.0%	6.7%	3.3%	2.9%	2.4%	2.1%	2.0%	1.9%
Wide-bandgap and ultra-wide-bandgap technologies for power management, distribution, and transmission*	6/10 2.04 medium	Chinese Academy of Sciences	39.8%	19.5%	7.0%	4.5%	4.3%	3.2%	1.8%	1.3%	1.3%	1.2%

What is ASPI's Critical Technology Tracker?

The Australian Strategic Policy Institute is the Indo-Pacific's leading defence, national security and technology think-tank. ASPI's *Critical Technology Tracker* (techtracker.aspi.org.au/) provides a rich dataset that allows users to track technologies fundamental to modern economies and societies' national security and defence, energy production, health and climate security. This research seeks 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. Another feature on the site is a 'talent tracker' which reveals the flow of global talent in these technologies and highlights brain gains and brain drains for each country. The *Critical Technology Tracker* and accompanying report (www.aspi.org.au/report/critical-technology-tracker) provide decision-makers with a new evidence base to make more informed policy and investment decisions. This effort goes further than previous attempts to benchmark research output across nations by focusing on individual institutions and technologies rather than on total research output.

Brief methodology

ASPI analysed the top 10% of the most highly cited papers to generate insights into which countries are publishing the greatest share of high-quality, innovative and high-impact research. Credit for each publication was divided among authors and their affiliations and not assigned only to the first author (for example, on a five-author paper, each author was attributed 20% credit). Fractional allocation of credit is a better prediction of individuals who go on to win Nobel Prizes or fellowship of prestigious societies. The contact address for each author was provided in the data downloaded from Web of Science. Web of Science (Core Collection) is heavily used by researchers who study scientific trends and it has well understood performance characteristics. We then built a bespoke data-processing pipeline to identify both the country of affiliation and the unique research institution name for each author. Building this pipeline and cleaning this large dataset took many months of work by dedicated data scientists before the data analysis could begin. For each technology, a custom search query was developed for the Web of Science database. This identified 2.2 million research papers subsequently used for analysis (the size of each technology category dataset analysed depends upon the technology being examined). For example, there were 526,738 research papers to analyse for machine learning (2018-2022), whereas post-quantum cryptography yielded a much smaller dataset of 4,416 papers. For the full and detailed methodology please visit aspi.org.au/report/critical-technology-tracker. In this update, there were multiple hospitals and cancer institutes within the biotechnologies category. The publications were aggregated for teaching hospitals and cancer institutes affiliated and funded by the parent universities as is often the case in the United States, Europe and China. The teaching hospitals in the UK are funded under the NHS trust and were treated as institutions separate to the parent universities.

Why research is vital for scientific and technological advancements

To build the Critical Technology Tracker, ASPI selected citations of scientific publications over many other data sources examined for potential inclusion. Among these other data sources were patent citations and patent ownership according to country. This is a rich source of insights, however determining the country of origin and ownership is a convoluted process, making reliable data insights a challenge. Similarly, analysis of venture capital funding could provide valuable insight into the degree of technical innovation. However, making consistent and reliable geographic inference from both patent and venture capitalist datasets is not as straightforward.

We selected research publications for our data analysis because they allowed us to build a high quality, reliable and global dataset. High-impact research is a major contributor to technological, scientific and commercial strength. The effect is most pronounced for high-quality papers (in this case, the most highly cited). For example, 80% of research papers in the top 0.01% of high-quality research are referenced in patents. 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. In stark contrast, those research reports in the bottom 50% are almost never cited in patents. Patents that directly reference research papers deliver 26% more commercial value than otherwise comparable patents that are disconnected from research. For more details, please visit: www.aspi.org.au/report/critical-technology-tracker.

What are critical technologies?

Critical technologies can be defined as current and emerging technologies with the capacity to significantly enhance, or pose risk to, a country's national interests, including its economic prosperity, social cohesion, and national security. This is the Australian Government's definition, and it's a good one that holds relevance for all countries. Today, critical technologies are the focus of geopolitical and strategic competition and our understanding of the critical technology ecosystem – from how to ensure reliable access, the current trajectory of technology development and where the next breakthroughs will occur (and in what) – is too limited. It's important that we seek to fill this gap, and we hope this project will make a contribution, so we don't face a future in which one or two countries dominate new and emerging industries (something that occurred in 5G technologies) and so countries have ongoing access to trusted and secure critical technology supply chains.

Technology definitions

Atomic clocks

Devices that keep time by measuring the frequency of radiation emitted or absorbed by selected atoms. Atomic clocks are the most accurate timekeeping devices known and are used (directly or indirectly) for tasks where measuring time with precision and consistency is essential. Applications for atomic clocks include active and passive navigation systems, processing financial transactions and synchronising telecommunications networks.

Genome and genetic sequencing and analysis

Tools and techniques for sequencing the human genome, plants, viruses and other living organisms, and for analysing and understanding the functions of those sequences. Applications for genomics and genetic sequencing and analysis include identifying the genes associated with specific diseases or biological functions, identifying new communicable diseases, crop and livestock breeding and predicting how effective drugs will be for different patients.

Genetic engineering

Tools and techniques for directly modifying one or more of an organism's genes. Existing techniques include CRISPR gene editing and molecular cloning. Applications for genetic engineering include making crops that are more productive or require less water, treating genetic diseases by replacing faulty genes with working copies and cell therapies that treat diseases by extracting, modifying and reimplanting patients' own cells.

Gravitational force sensors

Devices that detect minute changes in Earth's gravitational field. Applications for gravitational-force sensors include passive navigation enhancement and detecting mineral deposits, concealed tunnels and other subsurface features that create tiny variations in Earth's gravitational field.

Novel antibiotics and antivirals

Systems for identifying or designing new types of antibiotic and antiviral drugs that can treat bacterial and viral infections in humans and animals safely and effectively. New antibiotic and antiviral drugs must be continually developed and tested to ensure there are drugs available to treat both new infectious diseases and existing bacterial and viral diseases that are resistant to existing drugs. Examples include drugs to treat Methicillin-resistant Staphylococcus aureus (MRSA) and severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2).

Nuclear medicine and radiation therapy

Nuclear medicine uses radioactive substances to diagnose or treat diseases. Applications for nuclear medicine include imaging internal organs and tissues, viewing biological processes and using radiopharmaceuticals to treat cancers and other diseases. Radiotherapy uses ionising radiation to treat diseases by damaging the DNA in targeted cells, killing those cells. Applications for radiotherapy include treating some types of cancer and treating other diseases caused by overactive cells. While imaging and diagnosis techniques constitute a significant part of nuclear medicine, our publication dataset is focused on the application of these techniques to the diagnosis and treatment of diseases.

Inertial navigation systems

Systems and devices that can calculate the position of an object relative to a reference point without using any external references. Applications for high precision inertial navigation systems include replacing or augmenting other navigation systems that require continuous external references—like GPS—in places where external signals can be blocked, for example underground or in cities with narrow streets and tall buildings. Inertial navigation systems are more resistant to spoof and jamming attacks on GPS systems.

Magnetic field sensors

Devices that can detect and measure the strength and/or direction of magnetic fields. Applications for magnetic field sensors include passive navigation, imaging for health, metallurgy, scientific research and threat detection for defence.

Mesh network

A mesh or ad hoc network describes a network between multiple devices or 'nodes' that allows them to communicate in a closed network without the need for an internet connection. What separates mesh and ad hoc networks is their range needs and each node's internal capabilities; nodes (or devices) in a mesh network have the capability to send data **through** other nodes in the network for the data to reach their intended destination. The nodes within the network will calculate the most efficient path for data transfer based on data traffic and the nodes arrangement. Mesh networks are more time and labour intensive to set up initially but provide stable and robust connections. Ad hoc networks are as the name alludes to, networks of devices that can easily join or leave a closed network. Ad hoc networks are easier to configure compared to mesh networks. Unlike mesh networks, however, ad hoc devices/nodes cannot send data **through** individual nodes and are thus limited to data communication **to** devices within the range of the transmitting device. Both network topologies are useful under different conditions. Mesh networks are currently utilised for high-efficiency, high-speed data transfer, and both are utilised in the independent "offline" communication technology space.

Multispectral and hyperspectral imaging sensors

Multispectral imaging sensors capture data across a few bands across the electromagnetic spectrum, visible and non-visible spectra. Hyperspectral imaging sensors further this approach by capturing hundreds of bands continuously across the electromagnetic spectrum and map chemical content because of their specific spectral signatures. Applications for multispectral and hyperspectral imaging sensors include healthcare, defence, agriculture, minerals, forestry, and machine vision for autonomous vehicles and robots.

Radar

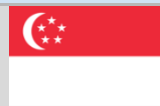
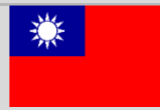
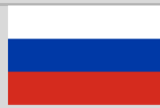
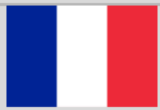
Systems that listen for radio waves and microwaves reflected off objects and surfaces—such as people, buildings, aircraft and mountains—to 'see' how far away and how fast those objects are moving. Active radar systems send their own radio signals to reflect off (for example, ground penetrating radar) whereas passive radar systems listen for radio signals sent by targets or reflections of signals already present in the environment (for example, radio astronomy signals). Applications for radar include weather forecasting, situational awareness, connected and autonomous vehicles, virtual and augmented reality systems, and defence.

Wide bandgap and ultra-wide band gap technologies for power management, distribution, and transmission

Wide bandgap (WBG) and ultra-wide bandgap (UWBG) semiconductors are the new frontier in semiconductor technology and are so termed due the energy difference between valence and conduction bands (bandgap). Currently, wide bandgap semiconductors are widely used in solid state lighting with white LEDs. Compared to silicon, WBG and UWBG semiconductors are essential for power electronics due to their ability to operate at higher temperatures as well as higher voltages. In addition, their higher switching speeds combined with their high power makes them ideal for making a complete radio system. Applications for WBG and UWBG devices include power inverters, blue LEDs and lasers, high electron mobility transistors with low switching losses.

*Shows newly added technologies and new data

Flags

Country	Flag	Country	Flag	Country	Flag
Algeria		India		Singapore	
Australia		Iran		South Korea	
Austria		Italy		Spain	
Brazil		Japan		Switzerland	
Canada		Malaysia		Taiwan	
China		Netherlands		Turkey	
Egypt		Norway		United Kingdom	
Germany		Pakistan		United States	
Finland		Russia			
France		Saudi Arabia