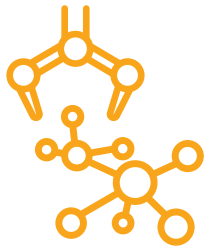
Advanced composite materials



New materials created by combining two or more materials with different properties, without dissolving or blending them into each other. Advanced composite materials have strength, stiffness, or toughness greater than the base materials alone.

Key Sectors

- Construction
- Defence and Defence Industry
- Energy
- Health
- Manufacturing
- Public Administration and Safety
- Space
- Transport and Logistics

Estimated impact on national interest	Low	Med	High
Economic Prosperity		X	
National Security		X	

Key Australian Government Actions

Initiatives

- The National Industry 4.0 Testlab in Composite Additive Manufacturing
- Recycling and Clean Energy National Manufacturing Priority road map
- Space National Manufacturing Priority road map
- Defence National Manufacturing Priority road map
- CSIRO Lab22

Regulations

- Defence and Strategic Goods List 2021

Example Outcomes

- Cheap and rapid manufacture of ultrathin and customisable antennas
- Stronger and lighter materials for aerospace and vehicle components and construction for improved performance and efficiency
- Improved orthopaedic and prosthetic devices for patients
- Safer storage and transport of hydrogen
- Detection of toxic gasses using small, light-weight and wearable sensing devices
- Compact remote, emergency distress beacons suitable for campers or hikers
- Increased durability and robustness for wearable personalised electronics
- More efficient CO_2 removal systems on submarines
- Increased reduction of thermal signatures of military vehicles and uniforms to decrease detection/increase stealth
- Composite structures for high temperature hypersonic applications for the aerospace and defence industries

Underpinning Science

ANZ Standard Research Classification

- Materials engineering
- Macromolecular and materials chemistry
- Aerospace engineering
- Automotive engineering
- Chemical engineering
- Mechanical engineering
- Biomedical engineering

Example Applications

Readiness Level – Now

- Strong, lightweight structures (e.g. aerospace vehicles, racing cars, sports equipment)
- Protective barriers (e.g. ballistic armour, heat shields, chemical barriers)
- High temperature resistant materials (e.g. for jet engines, particle accelerators, nuclear reactors, rocket nozzles)
- Industrial components (e.g. chemical storage tanks, pressure vessels, pumps)
- High energy transfer components (e.g. gear boxes, thermal and electrical conductors, automotive disc brakes)
- High endurance materials – wear resistant, corrosion resistant

Readiness Level – 2–5 years

- Integration of sense and detect capabilities (i.e. antenna metasurfaces) into composite structures – without the added weight of conventional antennae
- More resilient structures for use in space
- Increased commercial use of composites for industrial machinery and surface transportation as costs decline

Readiness Level – Beyond 5 years

- Long-endurance, high-speed flight
- Gas separation capabilities (e.g. gas masks and removal of low-concentration gases in confined spaces such as airplanes, submarines and space stations)
- Lighter, safer and more powerful batteries and fuel cells
- Integration of energy storage capabilities (e.g. batteries, supercapacitors and fuel cells) into composite structures - without the added weight of conventional storage systems
- Transparent barriers with desirable properties (e.g. electrically or thermally insulating, high strength, high temperature resistance)
- Structural materials for nuclear fusion reactors
- New CO_2 sequestration (or scrubbers) systems in submarines, or employment in respiratory canisters for adsorption of toxic chemicals, and various other circumstances

Australia's place in the world

Australia ranks 5th for research impact in this technology with Swinburne University of Technology ranked 7th globally. China has the highest research impact in this area and also has 3 institutions in the top 10 internationally—including the top institution, the Chinese Academy of Sciences—and the United States is second. Eight of Australia's research institutions are ranked in the top 50 internationally.

Germany has the highest venture capital (VC) investment ahead of the United States, while Australia is unranked. Internationally, VC investment has been decreasing by around 5% p.a. since 2016. Globally, the number of patents has been steady since 2015.

Given the sensitive nature of this technology much cutting-edge research is unlikely to be in the public domain, meaning this assessment may not be a true reflection of overall research capability. This assumption is also supported by the limited patent activity in this area. China has the greatest number of patents, more than triple that of 2nd ranked United States; Australia is ranked 18th.

Opportunities and Risks

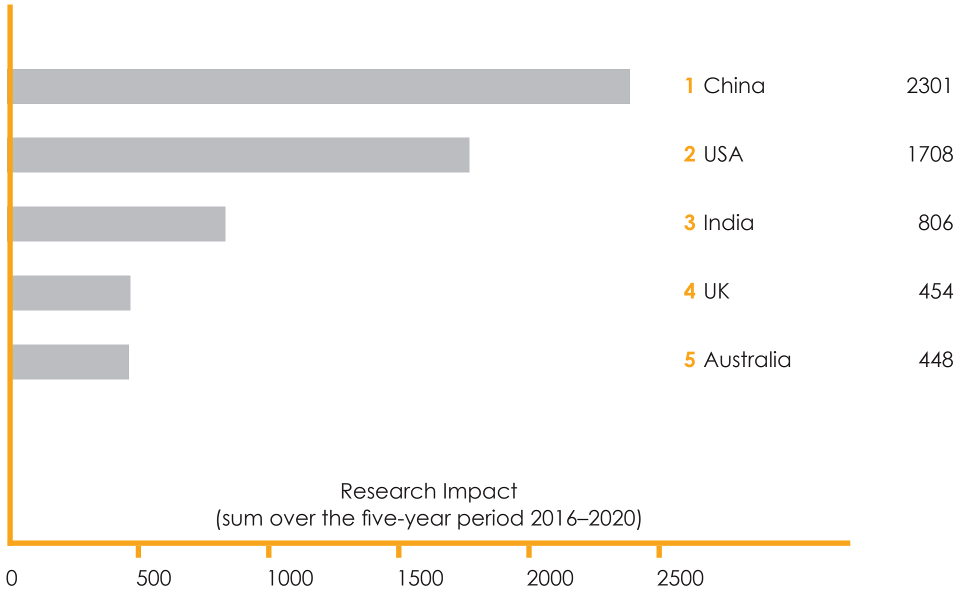
Advanced composite materials are an example of a niche, high-technology, high value-add form of manufacturing with a range of applications, and which also enable many other critical technologies. The Australian composites market was valued at $480 million in 2020, and is expected to grow to over $10 billion by the end of 2030. These materials may prove important for Australia's defence capabilities in aerospace and other operational requirements in equipment and vehicles. The importance of these materials is highlighted by their inclusion in each of the 2, 5 and 10 year success measures for research & development in the Space National Manufacturing Priority road map. Advanced composite materials are quickly becoming an important part of the clean energy and manufacturing sectors, and will play a role in energy transition; for example, new wind turbine blades, materials to reduce the weight of advanced vehicles and more efficient hydrogen storage.

Advanced composite materials are not without their drawbacks. Some materials require high levels of investment and expertise to produce. For example, Borophene—which can be used in next generation electronic devices, superior battery electrodes and safer hydrogen storage capabilities—is difficult and expensive to produce. Metal organic frameworks—which can be used in gas masks and removal of low-concentration gases in confined spaces—have issues with their stability, working capacity and scalability. Ongoing investment and effort is required to develop efficient and cost-effective production methods for these materials is essential in order to realise their potential benefits.

Applications for advanced composite materials can be very diverse and go beyond the original use they were designed for; this is often not obvious to inventors or manufacturers. These materials thus represent a potential espionage target, especially given their enabling capabilities for various military and security applications. Given Australia's relative strength in this area, it is a risk that must be carefully managed.

Research Impact (RI)

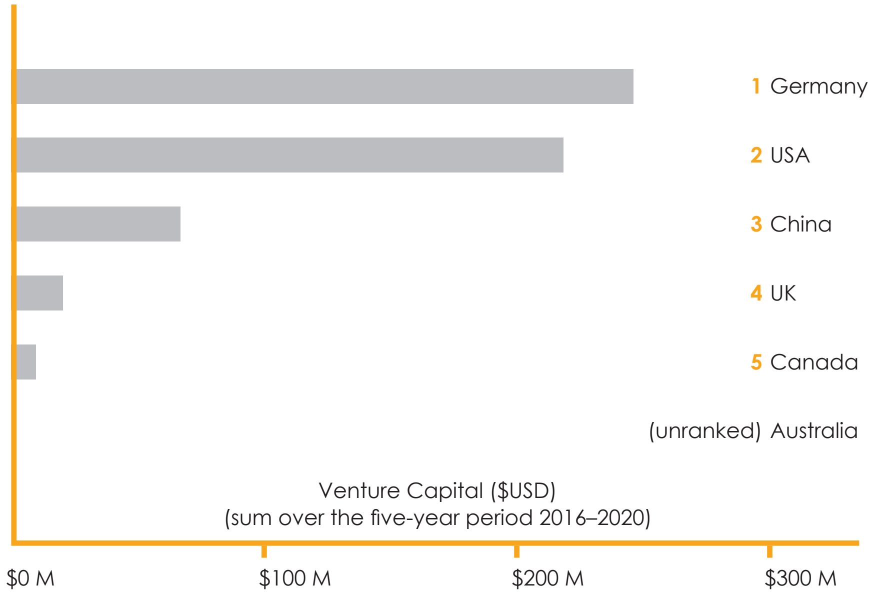
China has the highest research impact in this area, ahead of the United States. Australia is ranked 5th. Total volume of published research has been increasing at 7% p.a. over the 5 year period 2016–2020, with 21% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

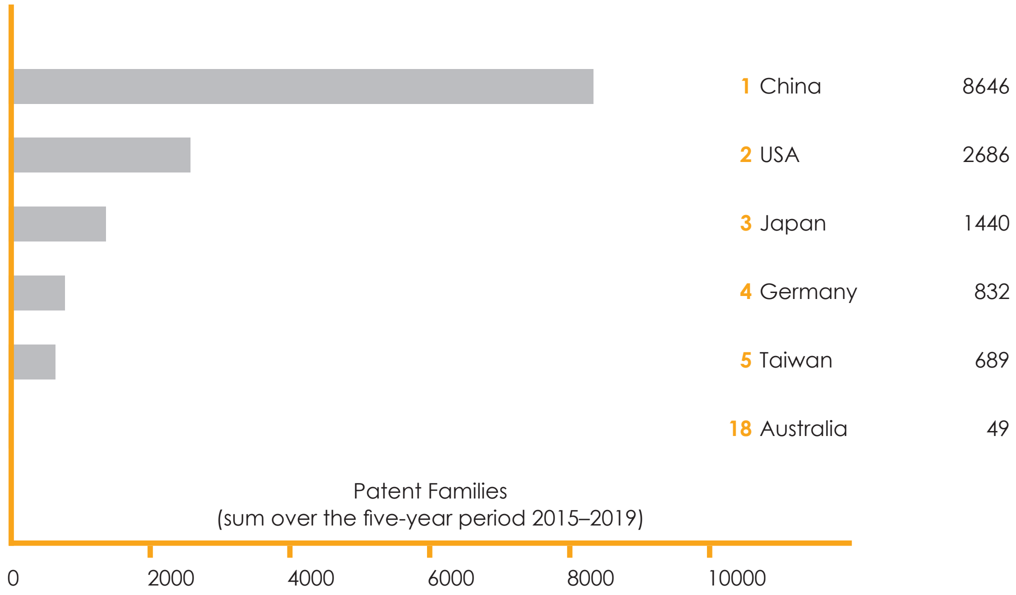
Germany has the highest amount of VC investment in advanced composite materials, ahead of the United States and China. Globally, investment in this area has been declining at around 5% p.a. since 2016. Australia is unranked.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents - International

The number of patents being lodged annually in this field has been steady since 2015. Most patents in this field were filed by applicants or inventors from China. Australia is ranked 18th.



Research Institutions - International

The top 10 international institutions for advanced composite materials are relatively diverse. China has 3 of the top 10, including the top ranked institution. Other countries with institutions in the top 10 include Algeria, Saudi Arabia, Singapore, Australia and the United States.

Rank	Top International Institution	Research Impact
1	Chinese Academy of Sciences | China	378
2	University of Sidi-Bel-Abbès | Algeria	250
3	King Abdulaziz University | Saudi Arabia	248
4	National University of Singapore | Singapore	230
5	Harbin Institute of Technology | China	206
6	University of Mascara | Algeria	179
7	Swinburne University of Technology | Australia	178
8	Zhejiang University | China	171
9	University of Tennessee, Knoxville | United States	153
10	NASA Langley Research Center | United States	143

Research Institutions - Australia

Within Australia, Swinburne University of Technology has the highest research impact and is ranked 7th internationally. The top 8 Australian institutions are in the top 50 internationally

Rank	Top Australian Institution	Research Impact
1	Swinburne University of Technology	178
2	University of Sydney	103
3	Monash University	90
4	University of New South Wales	52
5	Deakin University	46
6	University of Wollongong	41
7	Royal Melbourne Institute of Technology University	39
8	Australian National University	39
9	Queensland University of Technology	30
10	Defence Science & Technology Group	6

Patents - Australia

Top Australian Patent Applicants	Patent Families
Carbon Revolution	3
Boral IP Holdings	2
A number of Australian businesses have one patent family recorded in this technology area	

Patents filed by Australian businesses, 2015–2019.

Data current as at 16 March 2022.

Australian Government

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Advanced Explosives and Energetic Materials

Materials with large amounts of stored or potential energy that can produce an explosion. Applications for advanced explosives and energetic materials include mining, civil engineering, manufacturing and defence.

Key Sectors

- Construction
- Defence & Defence Industry
- Manufacturing
- Mining & Resources
- Space
- Transport & Logistics

Estimated impact on national interest	Low	Med	High
Economic Prosperity		X	
National Security			X

Key Australian Government Actions

Initiatives

- Critical Minerals Facility – providing $2 billion of loans for critical mineral projects supporting the Critical Minerals Strategy
- Critical Minerals Facilitation Office including 2019 Critical Minerals Strategy
- US-Australia Critical Minerals Plan
- Modern Manufacturing Strategy
- Sovereign Guided Weapons and Explosive Ordnance Enterprise

Regulations

- Defence and Strategic Goods List 2021
- Environment Protection and Biodiversity Conservation Act 1999

Example Outcomes

- Development of innovative and improved raw material extraction methods
- More efficient propellant for satellites (in terms of weight and energy)
- Reduced risk of uncontrollable, unintended or accidental explosions
- Decreased environmental impact during the use of advanced explosives and energetic materials
- Decreased sustainment costs for military weapons

Underpinning Science

ANZ Standard Research Classification Category

- Physical chemistry
- Geochemistry
- Chemical engineering
- Resources engineering and extractive metallurgy
- Classical physics

Example Applications

Readiness Level – Now

- Military weapons
- Shaped charges for controlled explosions, e.g. perforation of oil and gas wells
- Solid rocket motors for space system launch
- Propellant for satellite attitude control
- Solid propellant fire extinguishers and airbag inflation systems
- Solid propellant gas generators for emergency surfacing of ships
- Explosives for drilling and blasting to break rock for excavation in mining, construction and demolition
- Explosive rivets for aircraft manufacturing
- Explosive bonding of metals such as titanium and steel
- Fireworks
- Marine distress flares
- Decoy flares for defence assets
- Pyrotechnics for bird control at airports

Readiness Level – 2-5 years

- Low-impact emission rocket propellant for satellite launch
- 3D printed explosives
- High temperature explosives for hypersonic weapons

Readiness Level – Beyond 5 years

- Asteroid mining

Australia's place in the world

China has the highest research impact in this area and also has 6 institutions in the top 10 internationally, including the top 3. The United States is 2nd and Australia is ranked 13th. The United States has the highest venture capital (VC) investment ahead of the Republic of Korea, with Australia having the 5th highest amount of VC investment. Globally, the number of patents has been increasing at around 9% p.a. since 2015, with China having the greatest number of patents, more than double 2nd ranked United States; Australia is ranked 14th. Given the sensitive nature of this technology, much cutting-edge research is unlikely to be in the public domain, meaning this assessment may not be a true reflection of overall research capability.

China has considerable strength in research and patent filings in this area, well ahead of the United States and Australia. Australia's Defence Science and Technology Group leads national efforts in advanced explosives and energetic materials. Together with renewed focus on space exploration and with Government's $1 billion investment into guided weapons and explosive ordnance, domestic capability in this area is anticipated to expand.

Opportunities and Risks

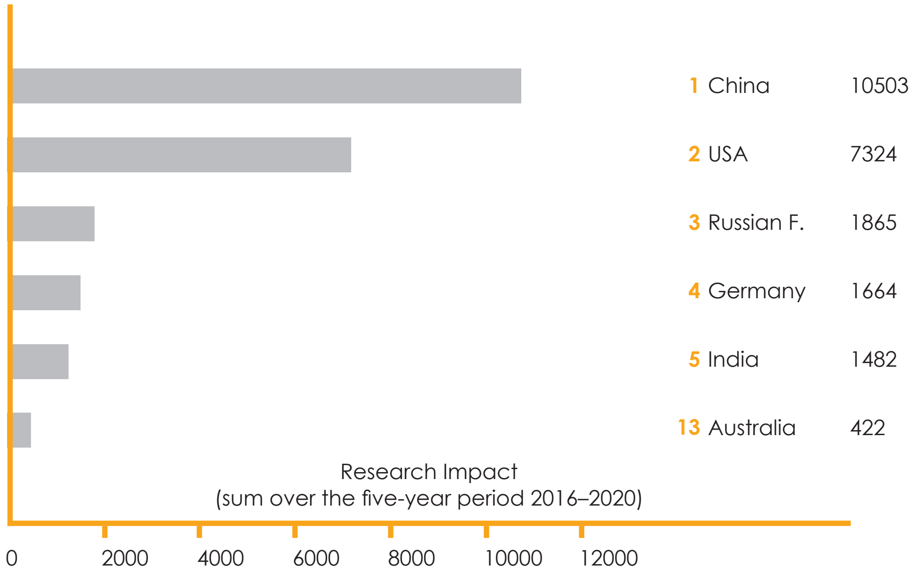
Advanced explosives and energetic materials are essential for construction, mining and space technology. Without continued access to these technologies, Australia would be limited in its ability to continue infrastructure projects, resource mining, housing development and more. The recent establishment of the Australian Space Agency creates opportunities to build domestic capability in space launch technologies, for example propellants, which may have applications in other areas, such as transport and logistics. Advancements in explosives and energetic materials, have the potential to create more directed and controlled explosions, improving safety and efficiency in the mining and resources sector.

Explosive ordnances are considered critical enablers for Australia's Defence Force. At present, Australia has $5.3 billion worth of explosive ordnance in inventory and imported over $160 million from the US in the last financial year. With this reliance on explosives and energetic resources for military purposes, Australia has the potential to obtain weapons security and export opportunities with domestic manufacturing and continued research in advanced materials. In recognition of this, the Commonwealth has been focusing on building sovereign capability in this sector.

Research and development in advanced explosives and energetic materials for weapons could be exploited by terrorists or criminal groups. However, export of these sensitive technologies are managed by measures, such as Defence Export Controls and the Defence Strategic Goods List, to ensure that risks of exploitation and misuse are reduced.

Research Impact (RI)

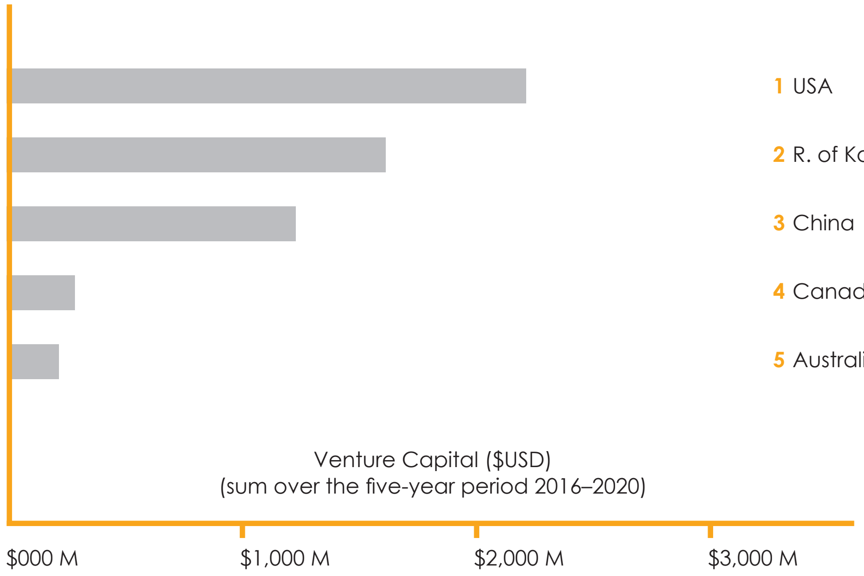
China has the highest research impact in this area, ahead of the United States, with Australia ranked 13th. Total volume of published research has been increasing at 5% p.a. over the 5 year period 2016–2020, with 11% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

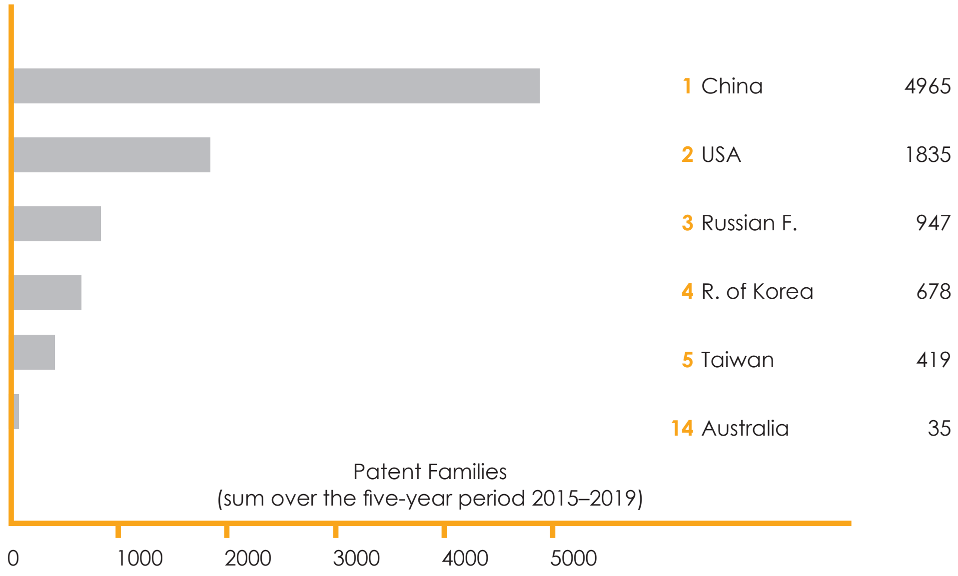
The United States has the highest amount of venture capital (VC) investment, ahead of the Republic of Korea and China. Australia is ranked 5th for VC investment for advanced explosives and energetic materials. Globally investment in this area has been increasing at 15% p.a. since 2016.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

The number of patents filed in this field has increased by 9% annually from 2015 to 2019. Most patents in this field were filed by applicants or inventors from China, ahead of the United States and the Russian Federation; Australia ranks 14th.



Research Institutions – International

China has 6 institutes in the top 10 international institutions, including the top 3 institutions. The United States, Germany and the Russian Federation make up the remaining institutes in the top 10 international institutions.

Rank	Top International Institution	Research Impact
1	China Academy of Engineering Physics | China	2050
2	Beijing Institute of Technology | China	1960
3	Nanjing University of Science and Technology | China	1813
4	University of Idaho | United States	1287
5	Xi'an Modern Chemistry Research Institute | China	1125
6	Naval Research Laboratory | United States	1014
7	Ludwig Maximilian University of Munich | Germany	703
8	Russian Academy of Sciences | Russian Federation	691
9	Southwest University of Science and Technology | China	594
10	Harbin Institute of Technology | China	583

Research Institutions – Australia

Within Australia, the University of Melbourne has the highest research impact. No Australian institution is in the top 50 international institutions.

Rank	Top Australian Institution	Research Impact
1	University of Melbourne	98
2	Monash University	48
3	Defence Science & Technology Group	44
4	Deakin University	39
5	Flinders University	29
6	Griffith University	25
7	University of South Australia	23
8	Royal Melbourne Institute of Technology University	23
9	Curtin University	17
10	Edith Cowan University	7

Patents – Australia

Top 5 Australian Patent Applicants	Patent Families
Dyno Nobel Asia Pacific	4
Bhattacharya, Utpal	2
CMTE Development	2
Commonwealth of Australia	2
Defendtex	2

Patents filed by Australian businesses, 2015–2019.

Australian Government

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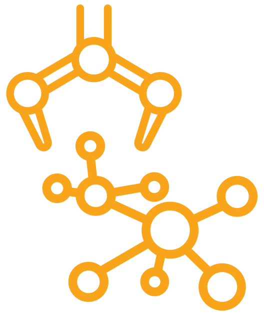
Critical minerals extraction and processing



Systems and processes to extract and process critical minerals safely, efficiently and sustainably. Australia has an abundance of critical minerals and has the opportunity to be a global leader in the ethical and environmentally responsible supply of key critical minerals. Applications for critical minerals extraction and processing include mining, concentrating minerals, and manufacturing battery-grade chemicals.

Key Sectors

- Health
- Energy & Environment
- Communications
- Defence & Defence Industry
- Transport & Logistics
- Mining and Resources
- Space

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security			X

Key Australian Government Actions

Initiatives

- Critical Mineral Facility – providing $2 billion of loans for critical mineral projects supporting the Critical Minerals Strategy
- Critical Minerals Facilitation Office including 2019 Critical Minerals Strategy
- Promotion of investment through the Australian Critical Minerals Prospectus
- US-Australia Critical Minerals Plan
- Modern Manufacturing Strategy
- METS Ignited - Industry Growth Centre | Mining in Australia
- Exploring for the Future (2016–2040), Geoscience Australia
- Global Resources Strategy

Regulations

- Defence and Strategic Goods List 2021
- Environment Protection and Biodiversity Conservation Act 1999
- Foreign Acquisitions and Takeovers Act 1975
- Foreign Investment Review Board

Australia's place in the world

Australia ranks 4th for research impact, led by the Curtin University of Technology, which ranks 37th internationally. China has five institutions in the top 10 internationally, with three institutes in the top five. Canada has the highest venture capital (VC) investment ahead of Sweden, with Australia having the 3rd highest amount of VC investment. Globally, the number of patents has been increasing at around 5% p.a., with China dominating the number of patent families, and Australia in 11th place.

Australia also has world-leading expertise in resource extraction and processing, high-tech engineering and renewables research, as evidenced by our high research ranking. In addition to significant reserves of lithium, cobalt, manganese, tantalum, tungsten, and zirconium, Australia is a global leader for rare earth elements deposits and production. Australia is also a highly attractive destination for investment, with competitive advantages across the full spectrum of technical, capital allocation, and risk considerations, including political and economic stability, technology, training, research and development, environmental and labour standards, and legal and regulatory certainty.

Example Outcomes

- Aim to ensure Australia becomes a supplier of processed critical minerals and capture more of the downstream processing supply chain
- Access to global market demand for critical minerals, including rare earth elements
- Reduced reliance on China as primary supplier of critical minerals including for energy (batteries) rare earth magnets, semiconductors and high-end defence requirements
- Development of innovative and improved raw material extraction methods, including reduced energy-intensity
- Development of improved recovery and recycling methods for obtaining materials from existing products
- Harness Australia's world-leading expertise in resources extraction and processing
- Increased investment in Australia's critical minerals sector and downstream processing

Underpinning Science

ANZ Standard Research Classification Category

- Resources engineering and extractive metallurgy
- Analytical chemistry
- Macromolecular and materials chemistry
- Physical chemistry
- Materials Engineering
- Geology
- Geochemistry

Opportunities and Risks

Technological change and advancement is driving the global demand for critical minerals that are essential for the production of high tech equipment, devices and consumables, including mobile phones and computers, flat-screen monitors, wind turbines, electric cars, solar panels, rechargeable batteries, defence industry technology and products, and many other high-tech applications. The importance of rare earth elements and other critical minerals stems from their unique catalytic, metallurgical, nuclear, electrical, magnetic, and luminescent properties.

As demand for critical minerals grows, there are economic opportunities for Australia. We have existing projects and significant geological reserves of minerals deemed critical by other nations and we are well placed to capitalise on rising global demand for secure supplies of critical minerals. Australia is one of the world's principal producers of several key major mineral commodities (e.g. bauxite, coal, copper, lead, gold, ilmenite, iron ore, nickel, rutile, zircon, and zinc), ores from which many critical minerals are also extracted as by-products. Given Australia's expertise in mining and metallurgical processing and extensive mineral resources, there is an opportunity for Australia to develop into a major, transparent and reliable supplier of processed critical minerals for the global economy, building our sovereign capability, delivering on our geopolitical requirements, and developing stronger regions. Based on a conservative estimate, Australia could add approximately $9.4 billion of value to mineral and metal production (currently valued at $112.2 billion, an increase of about 8%) from existing mines and favourable deposits.

Access to reliable, secure, and resilient supplies of critical minerals will increasingly underpin our prosperity and security, and those of our international partners. Critical minerals projects across the globe face a combination of market, technical and commercial risks. In particular, risks may arise if supply chains are highly geographically concentrated and for critical minerals these supply chains are already dominated by large buyers. Australia and like-minded partners support and promote diversified supply chains and markets to mitigate potential economic coercion and trade disruption risks.

There are a number of risks that may inhibit Australia's ability to develop into a supplier of processed critical minerals including: markets that suffer from small volumes, thin margins, opaque pricing and geopolitical risk; access to funding to invest in new critical minerals processing technology; the development of regulations and standards that ensure Australian critical minerals businesses remain globally competitive; insufficient knowledge of critical minerals in Australian deposits and their behaviour during metallurgical processing; limited geological studies dedicated to assessing and facilitating the discovery of critical mineral resources in Australia; the need for new mining technology and services to economically extract critical minerals; and gaps in capabilities of domestic smelters/refineries to process critical minerals.

Example Applications

Readiness Level – Now

- Geological data on critical minerals
- Raw ore and mineral processing
- Semi-automated and limited fully-automated mineral extraction
- Energy-intensive methods to separate rare earth elements

Readiness Level – 2–5 years

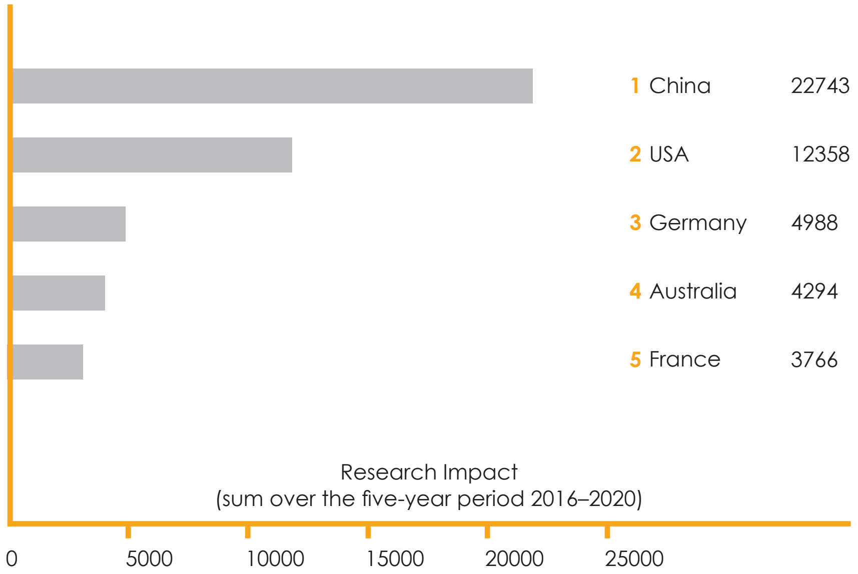
- Improved geological data and knowledge base of critical minerals
- Recycling electronic waste
- High value-add processing for alloys (e.g. rare earth elements)
- Improved geochemical association models of critical minerals to commodities
- Improved efficiency of mineral extraction and downstream processing

Readiness Level – Beyond 5 years

- Systematic mapping of Australia's mineral systems
- Next-generation drilling technology (safer, more environmentally friendly)
- Enhanced understanding of mineral processing behaviours
- Economically-viable separation of rare earth elements from by-products or co-products
- Automated processing for a wider variety of critical minerals
- Extraction of minerals from mining waste using plants that accumulate target metals (phytomining)
- Bio-remediation of mining waste

Research Impact (RI)

China has the highest research impact in this area, with Australia ranked 4th globally. The total volume of published research has been decreasing at around 9% p.a. over the 5 year period 2016–2020, with 32% of research involving international collaboration.



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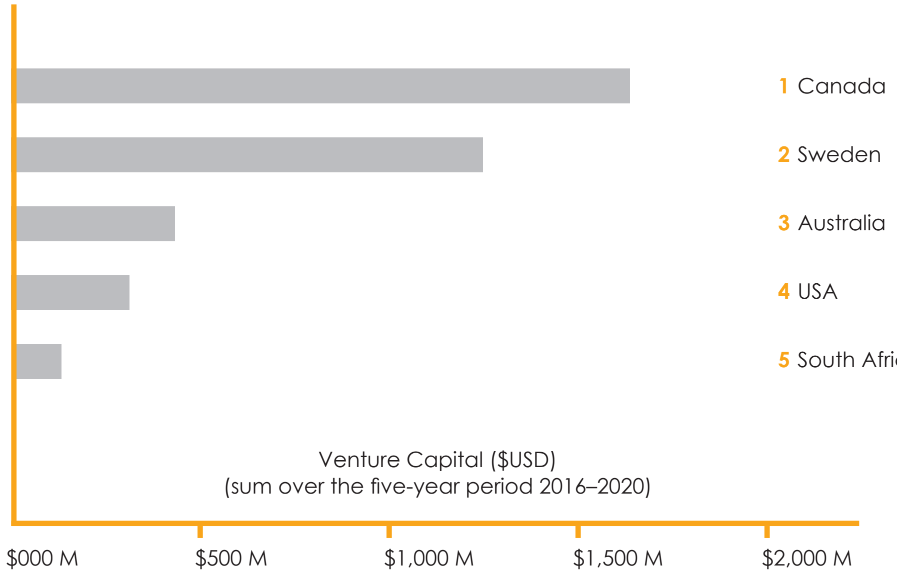
VC Investment

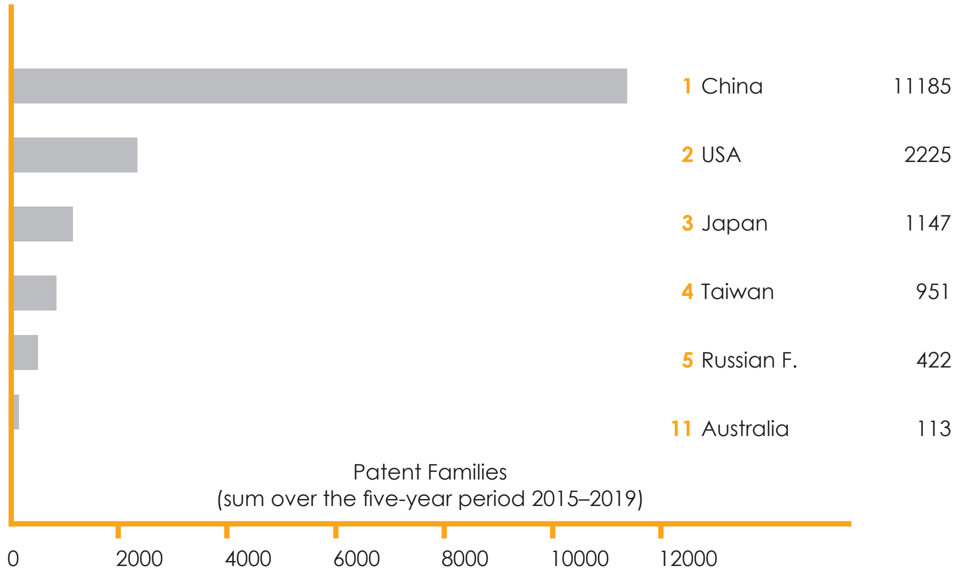
Australia is ranked 3rd for venture capital (VC) investment in this area, with Canada and Sweden having the greatest amounts of VC investment. Investment in this area has been growing at 19% p.a. since 2016.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

The number of patents filed annually in this field has increased by 5% from 2015 to 2019. Most patents in this field were filed by applicants or inventors from China, 5 times more than the United States. Australia ranks 11th, with the Australian Nuclear Science and Technology Organisation leading patent filings first filed in Australia by Australians.



Research Institutions – International

China has 5 institutes in the top 10 international institutions, with 3 in the top 5. French and Belgian institutes make up the rest of the top 5, and the United States has only 1 institute in the top 10.

Rank	Top International Institution	Research Impact
1	Chinese Academy of Sciences | China	4916
2	French National Centre for Scientific Research (CNRS) | France	2343
3	University of Chinese Academy of Sciences | China	1695
4	KU Leuven | Belgium	1177
5	Chinese Academy of Geological Sciences | China	1079
6	United States Department of Energy | United States	953
7	China University of Geosciences, Beijing | China	952
8	University of Science and Technology Beijing | China	931
9	Spanish National Research Council (CSIC) | Spain	903
10	Russian Academy of Sciences | Russian Federation	818

Research Institutions – Australia

Within Australia, Curtin University of Technology has the highest research impact. Australia has 3 institutes in the top 50 international institution: Curtin University of Technology (37th), University of New South Wales (48th) and University of Queensland (50th).

Rank	Top Australian Institution	Research Impact
1	Curtin University of Technology	501
2	University of New South Wales	451
3	University of Queensland	426
4	Monash University	359
5	Australian National University	338
6	University of Adelaide	331
7	CSIRO	324
8	University of Melbourne	261
9	Macquarie University	234
10	University of Western Australia	226

Patents – Australia

Top 5 Australian Patent Applicants	Patent Families
Australian Nuclear Science and Technology Organisation	7
Lithium Australia NL	5
Urban Mining Corp	5
Iluka Resources	4
Inneovation	4

Patents filed by Australian businesses, 2015–2019.

Australian Government

CTPCO
CRITICAL TECHNOLOGIES POLICY COORDINATION OFFICE

Advanced Optical Communication

Devices and systems that use light to transfer information over optical fibre or free space (i.e. air or the vacuum of space) and use laser technologies, adaptive optics and optical routing to transfer information faster, more reliably, more efficiently and/or using less energy. Applications for advanced optical communication include high-speed earth satellite communications, short-range visible light communications (i.e. 'Li-Fi'), narrow-beam laser communications and multi-gigabit broadband and corporate networks.

Key Sectors

Influences all sectors of the economy, including:

- Agriculture
- Banking & Finance
- Communications
- Defence & Defence Industry
- Energy & Environment
- Health
- Transport & Logistics
- Education & Research
- Mining & Resources
- Manufacturing
- Space

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security			X

Key Australian Government Actions

Initiatives

- Silicon Quantum Computing
- SmartSat CRC
- Telecommunications Security Review
- National Earth Observations from Space Infrastructure Plan (NEOS-IP)
- Advancing Space: Australian Civil Space Strategy 2019-2028
- Digital Economy Strategy

Regulations

- Australian Radiation Protection and Nuclear Safety Regulations 2018
- Telecommunications Act 1997
- Defence and Strategic Goods List 2021

Example Outcomes

- A more innovative and agile Australia through innovation development and information sharing
- Faster, more reliable and more equitable internet access
- Expanded digital economy
- Increased consumer benefits through improved connectivity
- Increased productivity through IoT and connected systems
- More resilient emergency management and enhanced rapid response capabilities
- Improved access to health and medical interventions through enhanced telehealth capability, especially for remote and regional communities
- Smart Cities and enhanced infrastructure and regional development through improved connectivity
- Improved access to interactive media and services, especially for remote communities
- Improved access experience for online education

Underpinning Science

ANZ Standard Research Classification Category

- Communications engineering
- Atomic, molecular and optical physics
- Classical physics
- Electronics, sensors and digital hardware
- Electrical engineering
- Cloud computing

Example Applications

Readiness Level – Now

- High speed fixed internet connectivity via optical fibre
- Fibre optic backbones for high speed mobile internet connectivity (4G/5G)
- High-bandwidth data centre interconnects supporting cloud services

Readiness Level – 2–5 years

- Very high bandwidth undersea telecommunication cables
- High bandwidth space-to-earth communications

Readiness Level – Beyond 5 years

- Space-to-earth communications for deep space exploration
- Ultra-fast computing with on-chip optical interconnects
- Secure communications for remote piloted and autonomous vehicle communications
- Fibre optic backbones for high speed mobile internet connectivity (6G)
- Low earth orbit (LEO) satellite constellations that offer high-bandwidth, low-latency internet access

Australia's place in the world

Australia ranks 10th for research impact, led by the University of Technology Sydney, which is ranked 29th internationally. China has the highest research impact, with 7 of the top 10 international institutions. Australia is unranked for venture capital (VC) investment, with the bulk of the VC investment in this area in the United States and the United Kingdom. The number of patents is increasing by around 4% p.a., with China having the greatest number of patent families, more than double that of the United States.

Several Australian companies specialising in optical communications have been highlighted by the Australian Space Agency for potential opportunities to be a part of projects that can support NASA's Moon to Mars program. These case studies highlight Australia's capability and competitiveness as part of the international space initiatives.

Opportunities and Risks

Compared to similarly advanced radiofrequency and copper-based technologies, optical communications technologies provide much higher bandwidth, reduced congestion and consume less power. The opportunity from advanced optical communications is enabling more people to each use more bandwidth, at the same time. Advanced optical communications may also support other technologies, such as photonic computing and optically based target and tracking systems, and laser development.

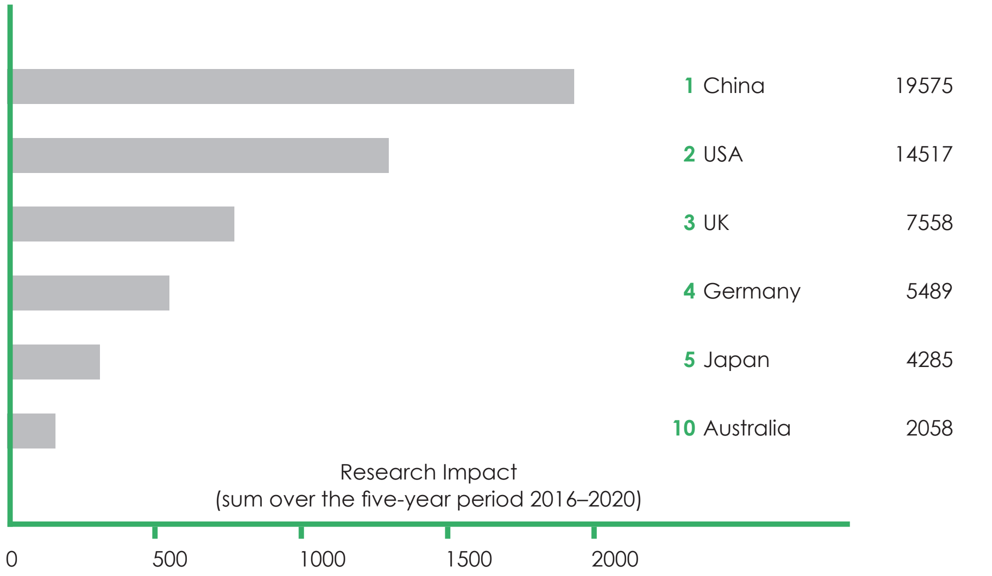
Advanced optical communications will power high-bandwidth, low-latency earth-space and space-space communications. Advanced optical communications technologies like Li-Fi could offer enhanced security while addressing the spectrum congestion issues faced by Wi-Fi. Advanced optical communications will continue to provide the backbone for Australia's telecommunications networks, including international telecommunications, communications between Australia's geographically dispersed population centres, and within the non-radio parts of 5G and 6G networks. Advances in optical communications can enhance the efficiency and lifespan of the submarine cables that carry the vast majority of Australia's international telecommunications traffic.

Developing greater expertise in optical communications opens the door to Australia designing or even manufacturing advanced optical communications devices. The greatest risk is that Australia will be almost entirely dependent on imported devices and expertise, which would leave Australia vulnerable to supply disruptions and potentially difficult security decisions.

Insufficient innovation may slow the growth of Australia's digital economy and limit the effectiveness of other critical technologies, such as advanced radiofrequency communications.

Research Impact (RI)

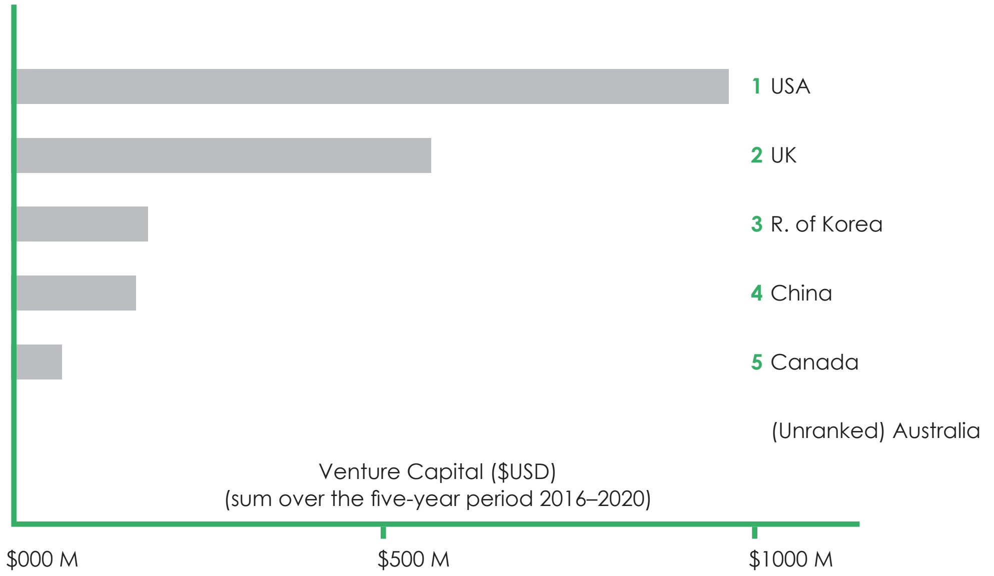
Australia ranks 10th worldwide for research impact in a field led by China and the United States. The total volume of research publications has increased at around 1% p.a. over the 5 year period 2016–2020, with 22% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

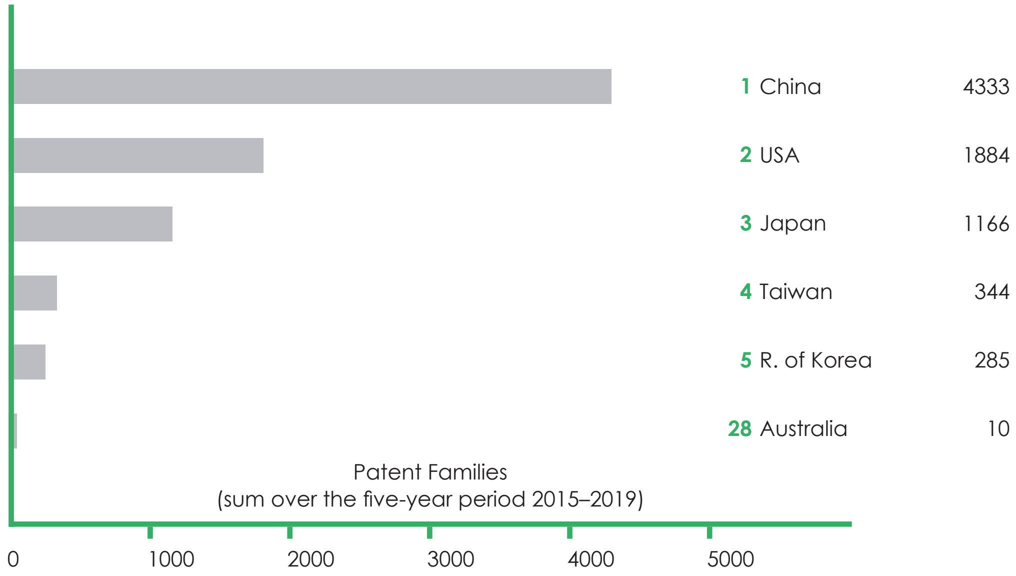
The United States has the highest amount of venture capital (VC) investment ahead of the United Kingdom (second highest). The Republic of Korea (3rd) and China (4th), have comparable amounts of relative venture capital (VC). Australia is unranked. Globally, VC investment in this area has been increasing at around 42 % p.a. since 2016.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

Most patents for this technology were filed by Chinese applicants or inventors, more than twice the number of the United States. Australia is ranked 28th. Overall patent applications have been increasing at 4% p.a. since 2015.



Research Institutions – International

China has 7 institutes in the top 10 international institutions, with the Chinese Academy of Sciences having the highest research impact. The other three institutes in the top 10 are from the United States, Saudi Arabia and France.

Rank	Top International Institution	Research Impact
1	Chinese Academy of Sciences | China	3050
2	Lucent | United States	1899
3	Beijing University of Posts and Telecommunications | China	1581
4	Huazhong University of Science and Technology | China	1578
5	Tsinghua University | China	1317
6	King Abdullah University of Science and Technology | Saudi Arabia	1274
7	Shenzhen University | China	1270
8	Shanghai Jiao Tong University | China	1210
9	French National Centre for Scientific Research (CNRS) | France	1198
10	Peking University | China	1193

Research Institutions – Australia

Within Australia, the University of Technology Sydney has the highest research impact nationally, and is ranked 28th internationally. The University of Sydney ranks 47th internationally.

Rank	Top Australian Institution	Research Impact
1	University of Technology Sydney	713
2	University of Sydney	556
3	University of Melbourne	538
4	Royal Melbourne Institute of Technology University	424
5	Monash University	265
6	Swinburne University of Technology	258
7	University of New South Wales	255
8	Australian National University	241
9	Edith Cowan University	107
10	Macquarie University	55

Patents – Australia

Top 4 Australian Patent Applicants	Patent Families
BAE Systems Australia	2
Biarri Networks	2
Baraja	1
University of Sydney	1

Patents filed by Australian businesses, 2015–2019.

Advanced Radiofrequency Communications

Devices and systems that use radio waves to transfer information over free space (i.e. air or the vacuum of space) and use novel modulation techniques, advanced antenna designs and beamforming technologies to transfer information faster, more reliably, more efficiently and/or using less energy.

Key Sectors

Influences all sectors of the economy, including:

- Agriculture
- Banking & Finance
- Communications
- Defence & Defence Industry
- Energy & Environment
- Health
- Transport & Logistics
- Education & Research
- Mining & Resources
- Manufacturing
- Space

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security			X

Key Australian Government Actions

Initiatives

- 5G - Enabling the Future
- 5G Test Beds
- 5G Innovation Initiative
- Digital Economy Strategy
- Telecommunications Security Review
- National Earth Observations from Space Infrastructure Plan (NEOS-IP)
- Advancing Space: Australian Civil Space Strategy 2019-2028
- SmartSat CRC

Regulations

- Radiocommunications Act 1992
- Telecommunications Act 1997
- Defence and Strategic Goods List 2021

Example Outcomes

- Greater capacity and lower latency, with a greater number of active devices
- Greater wireless connectivity drives growth of the digital economy
- Increased productivity through IoT and connected systems
- More resilient emergency management and enhanced rapid response capabilities
- Improved access to health and medical interventions through enhanced telehealth capability
- Smart Cities and enhanced infrastructure and regional development through improved connectivity
- Improved access to banking and financial services, especially for remote communities
- Improved access to online education through faster and more widely available broadband internet services and the emergence of tactile internet

Underpinning Science

ANZ Standard Research Classification Category

- Communications engineering
- Atomic, molecular and optical physics
- Electronics, sensors and digital hardware
- Distributed computing and systems software
- Classical physics
- Aerospace engineering
- Electrical engineering

Example Applications

Readiness Level – Now

- High speed broadband internet connectivity (4G and 5G)
- Wi-Fi and Bluetooth connectivity
- IoT connectivity
- Remote-piloted vehicle control and monitoring
- Machine connectivity for industry automation
- Satellite uplinks and downlinks
- Space communications
- Television and radio broadcasting services
- Dedicated government radio communications
- High bandwidth, low latency satellite communications for defence

Readiness Level – 2–5 years

- Ultra-low latency augmented reality and advanced simulations and models
- Improved industrial automation using 5G ultra reliable low latency communication enabled networks
- Consumer-ready and affordable low earth orbit (LEO) satellite constellations that offer high bandwidth and low-latency internet access
- Faster and more reliable Wi-Fi in dense environments, like apartment buildings

Readiness Level – Beyond 5 years

- Very-low-power, high efficiency IoT devices
- Real-time, mobile augmented and virtual reality
- Wireless body area networks through on-skin, under-skin and clothing to monitor patients, athletes, soldiers
- 6G ultra reliable low latency communication enabled smart traffic systems and autonomous vehicle communications

Australia's place in the world

Australia ranks 11th for research impact, led by the University of Technology Sydney, which ranks 27th internationally. While the United States has the highest overall research impact, China has 3 universities in the top 5 international institutions. The French National Centre for Scientific Research (CNRS) ranks highly for research impact across the advanced communications technologies—advanced radiofrequency and optical communication technologies.

The United States dominates venture capital investment in this area, ahead of second placed China. The number of patents is increasing by around 5% p.a., with China having the greatest number of patent families, slightly more than the USA.

Radiofrequency technologies, including 5G and communication satellites, are vital for Australian connectivity, and will underpin the digital economy and enable a more innovative and agile Australia. New South Wales, Queensland, Victoria, and Western Australia all have private-sector operated 5G innovation centres.

Opportunities and Risks

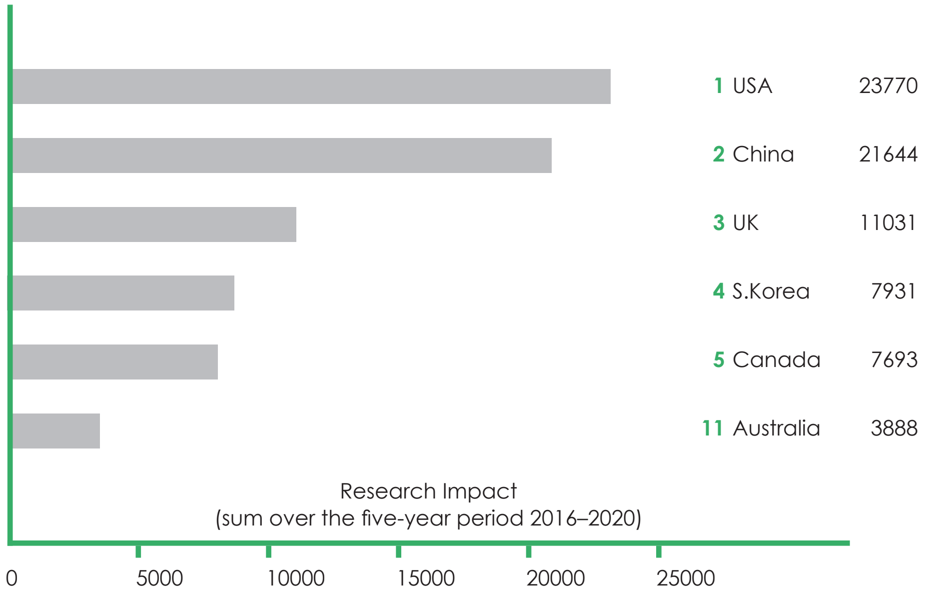
Australians depend on advanced radiofrequency communications and digital connectivity for economic, education and social activity. Devices and everyday objects are also increasingly dependent on advanced radiofrequency communications technologies for home and industry automation. While increased connectivity has benefits across all of society and the economy, there are increased risks associated with cyber security, data collection, protection, and privacy that are being actively addressed by government.

A significant risk for advanced communication technologies in Australia (including advanced radiofrequency and advanced optical communications) is related to access and supply chain security. Specifically, Australia is almost entirely dependent on overseas manufacturing and suppliers of advanced communications material and equipment. This is compounded by high supplier concentration with a small number of vendors dominating the market, some of which may not be from trusted international partners. As Australia's national security has significant reliance on high-bandwidth, secure market diversity and security will be important. Internationally, advanced communications technologies are highly dependent on a reliable supply of semiconductors. To address these risks the Australian government has established the Office of Supply Chain Resilience and the Supply Chain Resilience Initiative to develop tangible measures to mitigate these risks. Australia is also working with QUAD partners and other like-minds to identify trustworthy vendors, encourage vendor diversity and improve diversity and competitiveness in the market.

Ensuring adequate infrastructure and support of these technologies has the potential to improve productivity across all sectors, ensure we remain competitive in traditional areas, such as agriculture and health care, and improve competitiveness in emerging areas. However, if Australia has insufficient domestic expertise or capability in advanced radiofrequency communications technology we risk higher costs and delays for commercial and civilian applications, which could limit Australia's capacity to use other technologies that require faster and more reliable connectivity and communication.

Research Impact (RI)

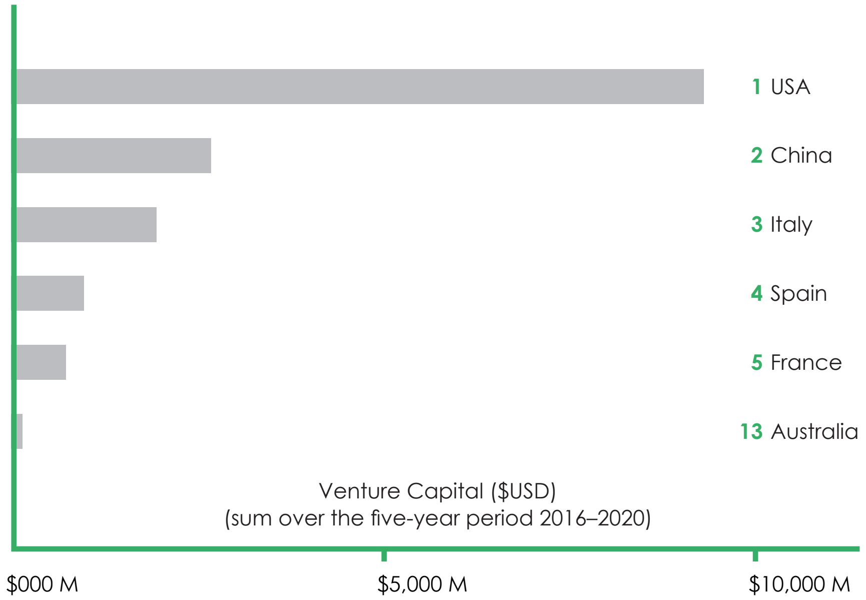
Australia ranks 11th for research impact in a field led by the United States and China. Total volume of published research has increased at around 7% p.a. over the 5 year period 2016–2020, with 7% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

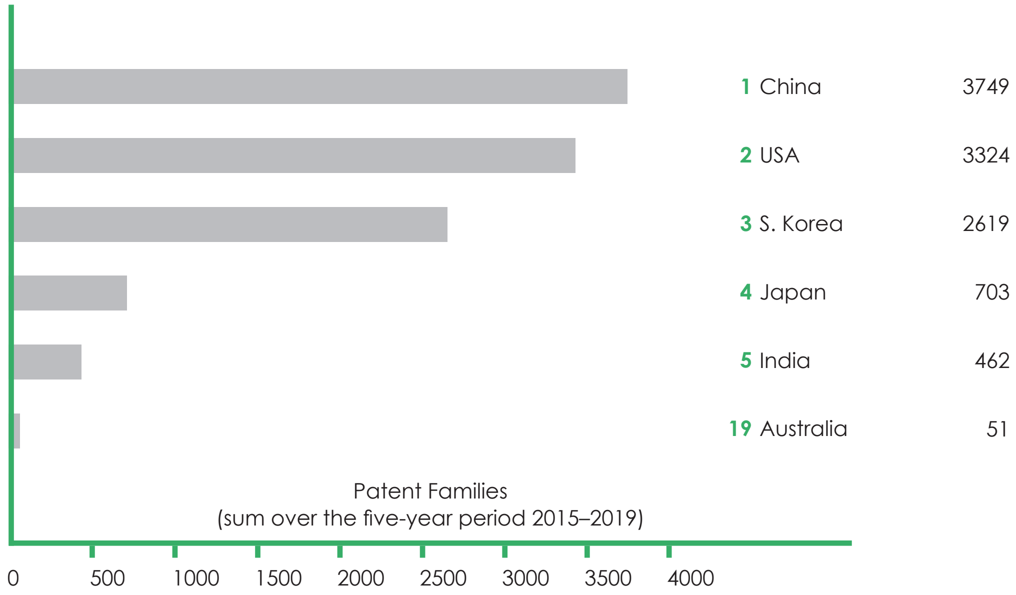
The United States dominates venture capital (VC) investment in this area with approximately 3 times the amount invested in China; Australia is ranked 13th. Investment globally in this area has been growing at around 44% p.a. since 2016.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

For this technology, most patents were filed by Chinese applicants or inventors, followed closely by the United States. Australia ranks 19th. Overall patent applications have been increasing at around 5% annually since 2015.



Research Institutions – International

China (3) and South Korea (2) make up the top 5 international institutions, led by Tsinghua University, for research impact.

Rank	Top International Institution	Research Impact
1	Tsinghua University | China	2583
2	University of Electronic Science and Technology of China | China	2261
3	Samsung | South Korea	2132
4	Sungkyunkwan University | South Korea	2084
5	Southeast University, Nanjing | China	1858
6	Nanyang Technological University | Singapore	1667
7	University of Southampton | United Kingdom	1630
8	French National Centre for Scientific Research (CNRS) | France	1556
9	University of Edinburgh | United Kingdom	1550
10	Lucent | United States	1476

Research Institutions – Australia

Within Australia, the University of Technology Sydney has the highest research impact, ranking 27th internationally. The University of Sydney and the University of New South Wales are ranked 40th and 45th, respectively, internationally.

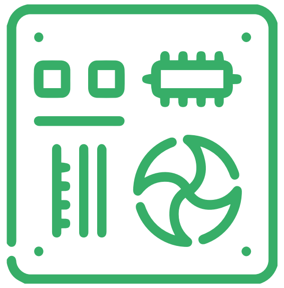
Rank	Top Australian Institution	Research Impact
1	University of Technology Sydney	833
2	University of Sydney	689
3	University of New South Wales	652
4	Royal Melbourne Institute of Technology University	592
5	University of Melbourne	288
6	Australian National University	265
7	Monash University	256
8	University of Wollongong	135
9	Macquarie University	97
10	CSIRO	72

Patents – Australia

Top 4 Australian Patent Applicants	Patent Families
Myriota (low Earth orbit nanosatellite provider)	2
Fleet Space Technologies (nanosatellite provider)	1
Nova Professional Services	1
Speedcast International (satellite provider)	1

Patents filed by Australian businesses, 2015-2019.

Advanced Data Analytics



Systems, processes and techniques for analysing large volumes of data (i.e. 'big data') and providing useful and timely insights, usually with limited human intervention. Applications for advanced data analytics include medical diagnosis and treatment, acoustic analytics, regulatory compliance, insurance, climate monitoring, infrastructure forecasting and planning, and national security.

Key Sectors

Influences all sectors of the economy, including:

- Agriculture
- Banking & Finance
- Communications
- Defence & Defence Industry
- Energy & Environment
- Health
- Transport & Logistics
- Education & Research
- Mining & Resources
- Manufacturing
- Space

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security			X

Key Australian Government Actions

Initiatives

- Australian Data Strategy
- Australian Cyber Security Growth Network
- Next Generation Technologies Fund & Defence Innovation Hub
- Biosecurity Advanced Analytics Capability

Regulations

- Privacy Act 1988
- Treasury Laws Amendment (Consumer Data Right) 2019

Example Outcomes

- Improved decision making across all sectors using pooled data
- More accurate risk assessments
- Improved public and individual health outcomes from predictive health models
- Improved processes and productivity in any industry from construction to tourism
- Enhanced recruitment and strategy development for sporting organisations and businesses
- Improved lean manufacturing processes to reduce waste and improve time efficiencies in monitoring and controlling the supply and demand of products and services
- Efficient management of equipment for mine operations
- Improved farm productivity, and adoption and commercialisation of research through targeted data that provides early intervention and actions for producers

Underpinning Science

ANZ Standard Research Classification Category

- Applied Mathematics
- Mathematical Physics
- Numerical and Computational Mathematics
- Software Engineering
- Data Management and Data Science
- Theory of Computation
- Quantum Physics
- Statistics

Example Applications

Readiness Level – Now

- Business and market intelligence, including targeted and customised advertising and recommendations
- Forecasting the spread of infectious diseases
- Risk modelling, credit ratings and fraud detection for financial institutions
- Bushfire prediction and analysis
- Cyber threat analysis
- Medical research and DNA analysis

Readiness Level – 2–5 years

- Predictive modelling of complex systems (traffic, energy, weather, climate change, public health, crime, financial markets, etc.) for enhanced decision making or early warning and response

Readiness Level – Beyond 5 years

- Human-machine symbiosis for enhanced decision making
- Accelerated scientific discovery – extraction of scientific knowledge directly from experimental data

Australia's place in the world

The United States and China are closely matched for research impact in this area, ranking 1st and 2nd respectively. Four of the top 5 international research institutes are in China. Advanced data analytics is an area in which Australia has considerable research strength. We are ranked 5th internationally for research impact, with the University of Wollongong ranked 3rd internationally. Australia has 5 institutes in the international top 50, including the University of Wollongong, University of Melbourne, University of Technology Sydney, University of New South Wales and the University of Sydney.

The United States has slightly more venture capital (VC) investment than India, and both have considerably greater investment than China (3rd). Australia ranks 16th globally, while worldwide VC investment has been increasing by around 49% p.a. since 2016. China has the greatest number of patents in this area, with more than 5 times that of the United States (ranked 2nd). Australia ranks 14th. Patents for advanced data analytics have increased by 22% p.a. since 2016.

India is also highly ranked for research impact (4th) and VC investment (2nd), consistent with their emerging strengths in data technologies.

Opportunities and Risks

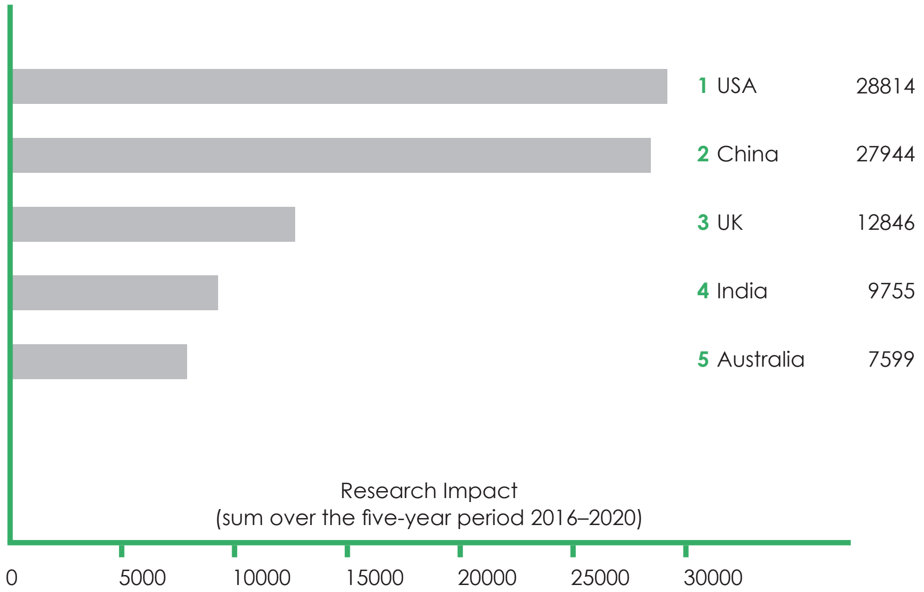
Advanced data analytics will have a significant impact on Australia's economic prosperity and national security. The ability to efficiently analyse large data sets to identify useful patterns and trends, using machine learning, will underpin faster and more responsive decision making across society. For example, the ability to analyse datasets for population groups will help identify those at risk of environmental or heritable health risks. Data analysis will also contribute to farm productivity through better informed cropping, chemical usage and livestock management; greater use of data will provide more efficient processes and management across all sectors. In turn, advanced data analytics will result in increased operational efficiency and reduced operating costs across sectors, increasing our economic prosperity.

Whilst large data sets are invaluable for identifying trends and insights to improve decision making and forecasting, poor decision making and unwanted outcomes may result from biased or incomplete data, or poor analysis of the data, with impacts ranging from minor inconvenience to physical harm. Cyber security risks, including data security, privacy and identity theft, need to be addressed wherever large sets of data are collected and used. National and international initiatives are setting standards and frameworks to address and mitigate these risks, together with improved public awareness, consumer data-empowerment, and understanding of data collection, usage, privacy and security. Measures are also necessary to ensure that capabilities to accurately profile and measure sentiment in individuals and targeted groups are not used to undermine Australia's social cohesion and democratic values.

In addition to the identified risks associated with data analytics, in order to realise the benefits of our research strengths, we need to ensure we have adequate data infrastructure to collect, store, manage, access, share and analyse large volumes of data.

Research Impact (RI)

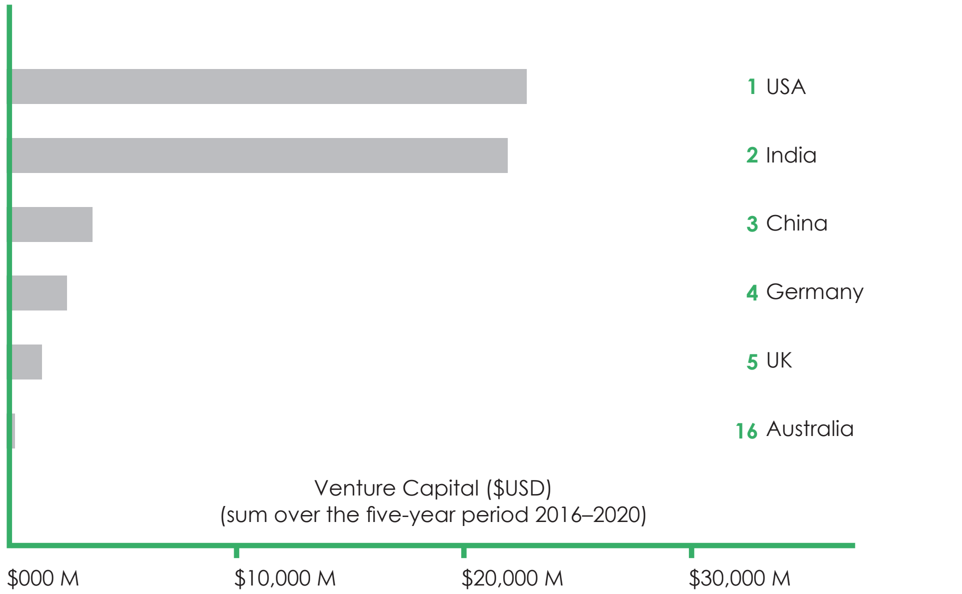
The United States has the highest research impact in this area, just ahead of China, with Australia ranked 5th. Total volume of published research has been increasing at around 7% p.a. over the 5 year period 2016–2020, with 21% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

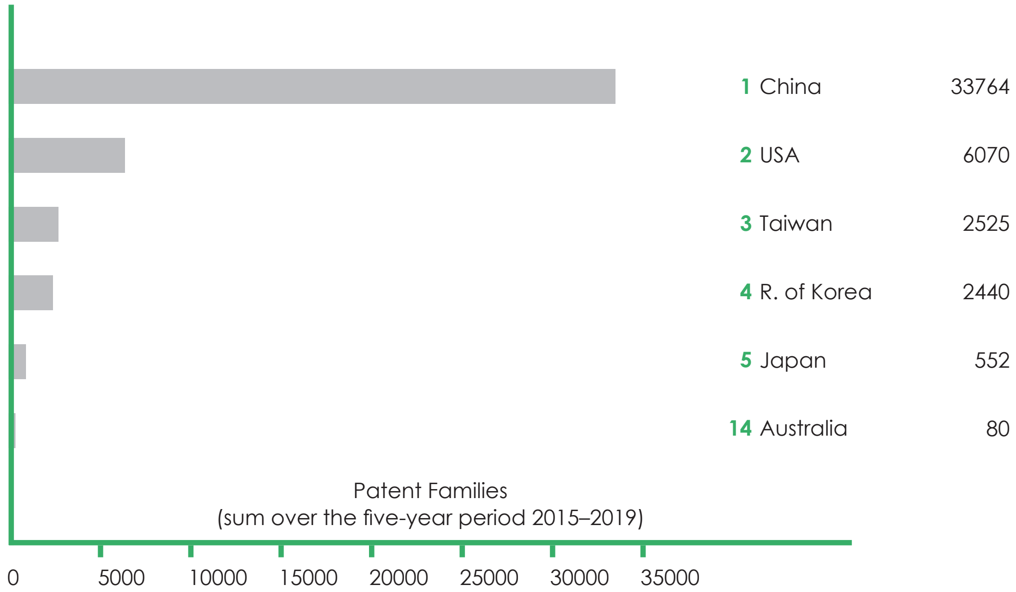
The United States has slightly more venture capital (VC) investment than 2nd ranked India, well ahead of China and Germany. Australia is 16th for VC investment for advanced data analytics. Investment in this area has been growing at 49% p.a. since 2016.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

The highest number of patents in this technology were filed by applicants or inventors in China with more than five times the number of the United States. Overall patent applications have been increasing at 22% annually since 2015. Australia ranks 14th.



Research Institutions – International

China has four of the top 10 research institutions, all in the top 5. The University of Wollongong is ranked 3rd internationally.

Rank	Top International Institution	Research Impact
1	Chinese Academy of Sciences | China	2029
2	Shanghai Jiao Tong University | China	1546
3	University of Wollongong | Australia	1395
4	Beihang University | China	1345
5	Tsinghua University | China	1332
6	Université Fédérale Toulouse Midi-Pyrénées | France	1282
7	King Saud University | Saudi Arabia	1199
8	Norwegian University of Science and Technology | Norway	1194
9	Hong Kong Polytechnic University | Hong Kong	1024
10	French National Centre for Scientific Research (CNRS) | France	1017

Research Australian – Australia

Within Australia, the University of Wollongong has the highest research metric, and is ranked 3rd internationally. The top 5 Australian institutes are all ranked in the top 30 internationally. The University of Melbourne is 12th, University of Technology Sydney 21st, University of New South Wales 25th and the University of Sydney 27th.

Rank	Top Australian Institution	Research Impact
1	University of Wollongong	1395
2	University of Melbourne	980
3	University of Technology Sydney	748
4	University of New South Wales	710
5	University of Sydney	694
6	Deakin University	506
7	CSIRO	473
8	Swinburne University of Technology	409
9	Monash University	311
10	Macquarie University	128

Patents – Australia

Top 5 Australian Patent Applicants	Patent Families
Data One Technologies	2
Pacbyte Software	2
Absolutist Technologies	1
CSIRO	1
Cellos Software	1

Patents filed by Australian businesses, 2015–2019.

Australian Government

CTPCO
CRITICAL TECHNOLOGIES POLICY COORDINATION OFFICE

Artificial intelligence (AI) algorithms and hardware accelerators

Artificial intelligence (AI) algorithms are computer algorithms that perform tasks normally requiring human intelligence. AI hardware accelerators are computer hardware optimised and purpose built to run algorithms faster, more precisely or using less energy than is possible using non-optimised general purpose computer hardware.

Key Sectors

Influences all sectors of the economy, including:

- Agriculture
- Banking & Finance
- Communications
- Defence & Defence Industry
- Energy & Environment
- Health
- Transport & Logistics
- Education & Research
- Mining & Resources
- Manufacturing
- Space

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security			X

Key Australian Government Actions

Initiatives

- AI Action Plan
- Digital Economy Strategy
- National Manufacturing Strategy
- DESE Digital Technologies Hub
- Cyber Security Strategy 2020
- CSIRO Data61 AI and ML Future Science Platform
- AI Ethics Framework

Regulations

- Competition and Consumer Act 2010
- Defence and Strategic Goods List 2021

Example Outcomes

- Fast, automated analysis of medical imaging
- Real-time decision support and expert systems across all sectors
- Faster and more detailed weather and climate models
- High efficiency, high reliability radio communications
- Low power 'smart' sensors
- Commodification of automated live language translation and captioning
- Privacy-preserving, energy efficient on device machine vision and speech recognition
- Real-time, high-resolution machine vision and object classification
- Significant energy and time savings for machine learning tasks

Underpinning Science

ANZ Standard Research Classification Category

- Applied computing
- Applied mathematics
- Artificial intelligence
- Computer vision and multimedia computation
- Data management and data science
- Electrical engineering
- Electronics, sensors and digital hardware
- Machine learning
- Materials Engineering
- Pure mathematics
- Software engineering
- Theory of computation

Example Applications

Readiness Level – Now

- New products, particularly computing components, systems and processes created by AI and which can be patented
- Virtual assistants
- Energy-efficient on-device speech-to-text
- Robots navigating simple human environments
- Synthetic data and deepfakes
- Cyber security defence

Readiness Level – 2–5 years

- Smart weapons
- Autonomous cyber security for defence
- High-speed computer vision for vehicles and drones
- Personalised online learning
- Creating high quality synthetic data to train machine learning models on
- On-device natural language processing
- On-sensor media processing
- Multiple AI systems working together

Readiness Level – Beyond 5 years

- Neuromorphic computing
- Physical autonomous assistants
- Learn-by-watching systems
- Artificial general intelligence
- Training new machine learning models entirely on a portable device
- Fully self-driving vehicles

Australia's place in the world

Australia ranks 15th globally for research impact, led by the University of Melbourne. The United States has the highest research impact for artificial intelligence, with seven of the top 10 performing research institutions, 4 of which are private companies. The United States has significantly higher amounts of venture capital (VC) investment compared to second ranked China. Australia is unranked, globally, for VC investment. Patent activity has been increasing at around 36% p.a. since 2016, with near equal global leaders China and the United States both holding approximately 100 times more patent families than Australia, which ranks 21st worldwide.

Artificial intelligence is being advanced in multiple Australian industry sectors, particularly in banking & finance, transport & logistics, communications and health. Australia is currently world leading on the development and deployment of AI Ethics Principles and has piloted these principles with 6 companies. Australia is a member of the Global Partnership on Artificial Intelligence (GPAI) and the AUKUS (Australia, United Kingdom, United States) alliance has an emphasis AI collaboration.

Opportunities and Risks

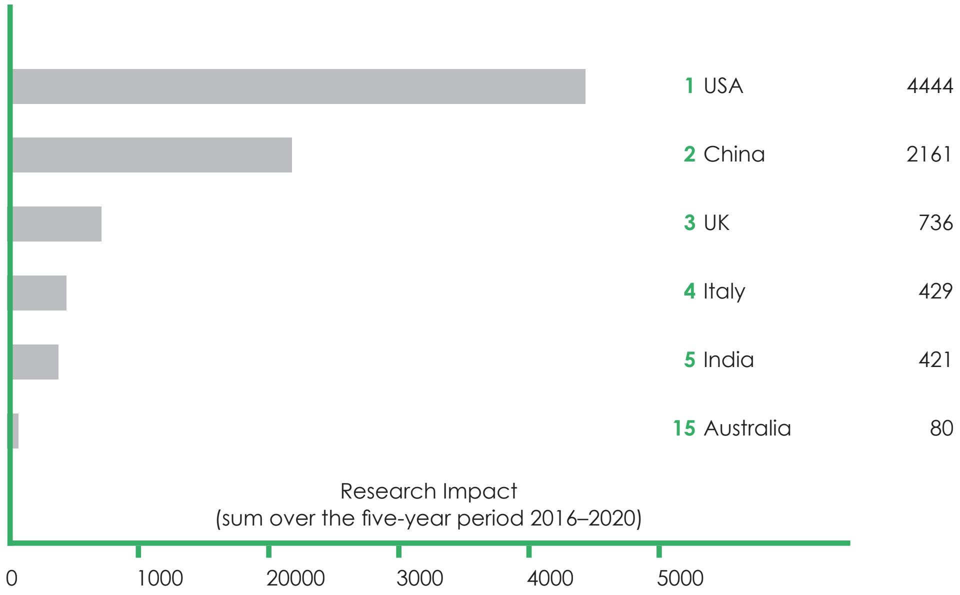
Artificial intelligence (AI) holds great promise for Australia's economy, security and society, from improved productivity through increased automation, enhanced cyber security, and increased worker productivity and fulfilment by allowing workers to focus on more creative or high value-add tasks. Building AI capability in Australia will help elevate Australia to a world-leading digital economy, and raise our position in the development and adoption of AI. AI capability also ensures we are able to counter national security threats, and increase our defence capabilities, through smarter military systems and operations.

With the opportunities AI promises, there are also significant risks. AI developed from poorly written or applied algorithms and biases can result in faulty decision-making that could harm people, machinery or critical infrastructure. Furthermore, poorly implemented algorithms can give rise to security issues.

AI can also be used to mount malicious cyber-attacks or spread AI-generated synthetic media (deepfakes) and mis/dis-information at unprecedented scale. Vulnerabilities in AI-based systems can also be exploited to undermine public confidence in AI-based tools and services. Australia is working with international like-minded partners to mitigate these risks.

Research Impact (RI)

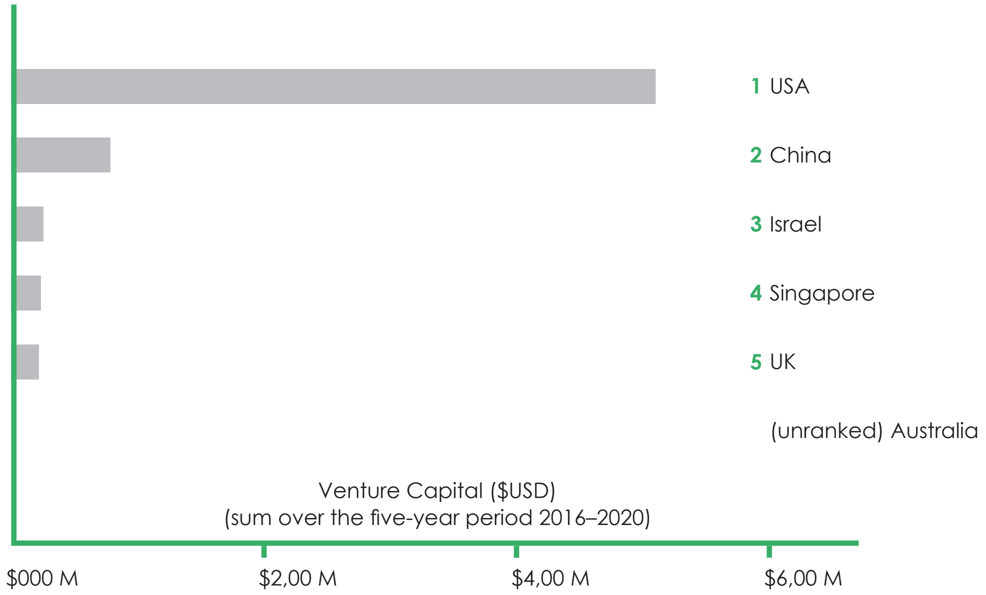
The United States has the highest research impact in this area, with Australia ranked 15th globally. Total volume of published research has increased at around 15% p.a., over the 5 year period 2016–2020, with 19% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

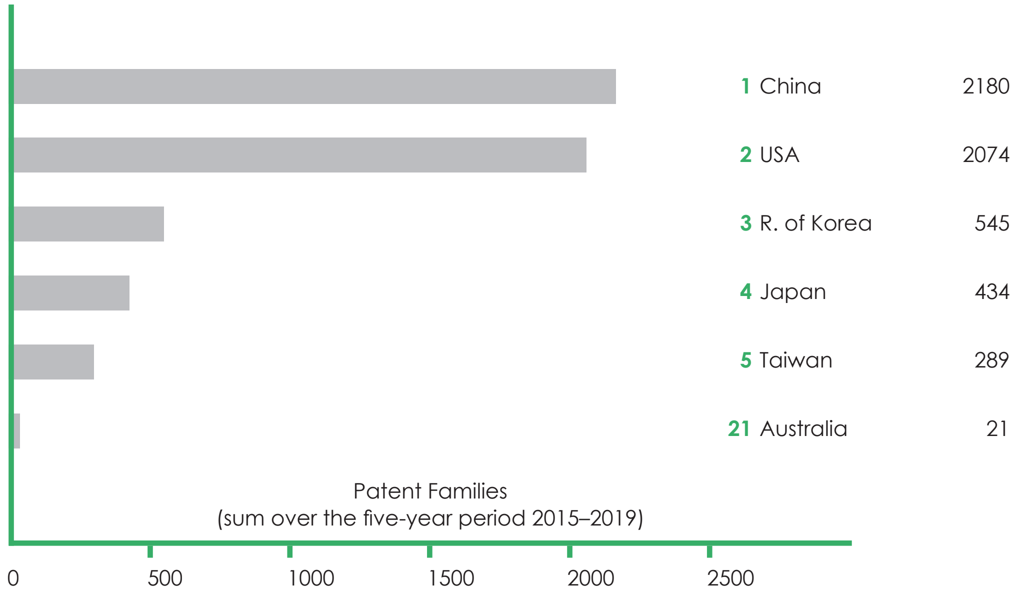
Australia is unranked for relative venture capital (VC) investment in this area, while the United States has the highest amount of investment in this area. Investment in this area has been growing at 16% p.a. since 2016.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

The number of patents filed annually in this field has increased by 36% from 2015 to 2019. Most patents in this field were filed by applicants or inventors from China and the United States. Australia ranks 21st.



Research Institutions – International

The United States has 7 institutes in the top 10 international institutions, including several private companies, Nvidia, Hewlett-Packard, IBM and Intel.

Rank	Top International Institution	Research Impact
1	Nvidia | United States	846
2	Tsinghua University | China	776
3	Hewlett-Packard | United States	764
4	Massachusetts Institute of Technology | United States	587
5	University of California at Santa Barbara | United States	519
6	Chinese Academy of Sciences | China	458
7	IBM | United States	457
8	Intel | United States	421
9	Huazhong University of Science and Technology | China	245
10	Stanford University | United States	233

Research Institutions – Australia

Within Australia, the University of Melbourne has the highest research impact.
No Australian institute is ranked in the top 50 international institutions.

Rank	Top Australian Institution	Research Impact
1	University of Melbourne	25
2	Queensland University of Technology	17
3	University of Sydney	12
4	Monash University	10
5	University of Technology Sydney	9
6	University of Adelaide	7
7	Southern Cross University	3
8	University of Queensland	2
9	Macquarie University	2
10	Deakin University	1

Patents – Australia

Top 5 Australian Patent Applicants	Patent Families
Ocean Logic	2
n/a (private citizen applicants only)	1
University of Sydney	1
n/a (private citizen applicants only)	1
Commonwealth of Australia	1

Patents filed by Australian businesses, 2015–2019.

High performance computing

Computer systems that exceed the performance capabilities of consumer devices (i.e. widely available desktop and laptop computers) by an order of magnitude.

Key Sectors

Influences all sectors of the economy, including:

- Agriculture
- Banking & Finance
- Communications
- Defence & Defence Industry
- Energy & Environment
- Education & Research
- Health
- Manufacturing
- Mining & Resources
- Space
- Transport & Logistics

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security			X

Key Australian Government Actions

Initiatives

- National Collaborative Research Infrastructure Strategy (NCRIS)
- The Digital Economy Strategy
- The International Cyber and Critical Technology Engagement Strategy
- Australia's Cyber Security Strategy 2020
- Department of Defence IIP Project ICT-2286

Regulations

- Nil

Example Outcomes

- Improved Government decision making through enhanced data analysis and manipulation capacity
- Increased capacity for pre-emptive bushfire prevention using sophisticated models
- Better performance of big data workloads domestically, reducing the need to transfer them overseas
- Improved traffic management in major cities during peak-hour across modes of transport
- High throughput, rapid data analysis, locally and as part of international consortia to inform the public health response during the COVID-19 pandemic
- Improved cyber security capabilities through complex data analytics at scale
- Greatly enhanced research productivity and research opportunity only possible on high performance computers

Underpinning Science

ANZ Standard Research Classification Category

- Artificial intelligence
- Applied computing
- Bioinformatics and computational biology
- Classical physics
- Computer vision and multimedia computation
- Data management and data science
- Distributed computing and systems software
- Fluid mechanics and thermal engineering
- Numerical and computational mathematics
- Theoretical and computational chemistry

Example Applications

Readiness Level – Now

- Processing data provided by autonomous cars to improve obstacle detection and avoidance
- Predictive analysis of financial markets and identify risk and opportunities
- Medical and biological research – including the study of emerging diseases
- Discovery of novel materials, chemicals and drugs
- Climate pattern modelling and weather forecasting
- Modelling and simulation of aerodynamics, nuclear, and quantum systems
- Oil and gas exploration via geoscientific simulations
- Air traffic management systems
- Training machine learning models
- Defence research, including AI, and in support of major defence acquisitions

Readiness Level – 2–5 years

- Supercomputers optimised for machine learning and data analytics to assist with complex decision making at scale
- Extensive public transport and crowd management systems
- Cyber-range and simulation platforms for effective human and AI collaboration in cyber security
- Ability to utilise increasing transport data flows to improve real-time and predictive traffic management capacities

Readiness Level – Beyond 5 years

- Neuromorphic supercomputers that can emulate a majority of the human brain's functions
- Cloud and edge computing capabilities that match top supercomputers
- Hybrid quantum and classical computing systems

Australia's place in the world

Australia ranks 13th globally for research impact, led by the University of Sydney, but no Australian research institutions are in the top 50 internationally. The United States dominates in overall research impact, over double the ranking of the next highest nation, China. The US has 7 out of 10 of the top ten ranked institutions. China has 2 research institutions in the top 5, including the highest ranked, and France has one.

The United States has the highest amount of venture capital investment, approximately double that of China. Australia is ranked 8th and VC investment in this field has been increasing at around 23% p.a. since 2016.

The number of patents lodged annually is increasing by around 1% p.a. China has the most patent families, closely followed by the United States.

Australia has invested significantly in HPC infrastructure and has the skilled workforce required to realise the benefits of this technology. The National Computing Infrastructure at the Australian National University is the fastest super computer in the southern hemisphere. The machine is used to perform medical research, climate simulations, astronomy workloads, and more.

Opportunities and Risks

High Performance Computing (HPC) can be leveraged to provide diverse commercial, geopolitical and research advantages, and is a useful asset for policymakers, scientists and innovators. While HPC extends existing capabilities, the potential advantages are vast and include cryptographic capabilities to respond to and carry out cyber operations, highly accurate economic and environmental predictions, and eventually, emulation of the human brain. HPC will also enable Australian businesses to solve complex computational problems using cloud-based infrastructure and more abundant and richer data sources.

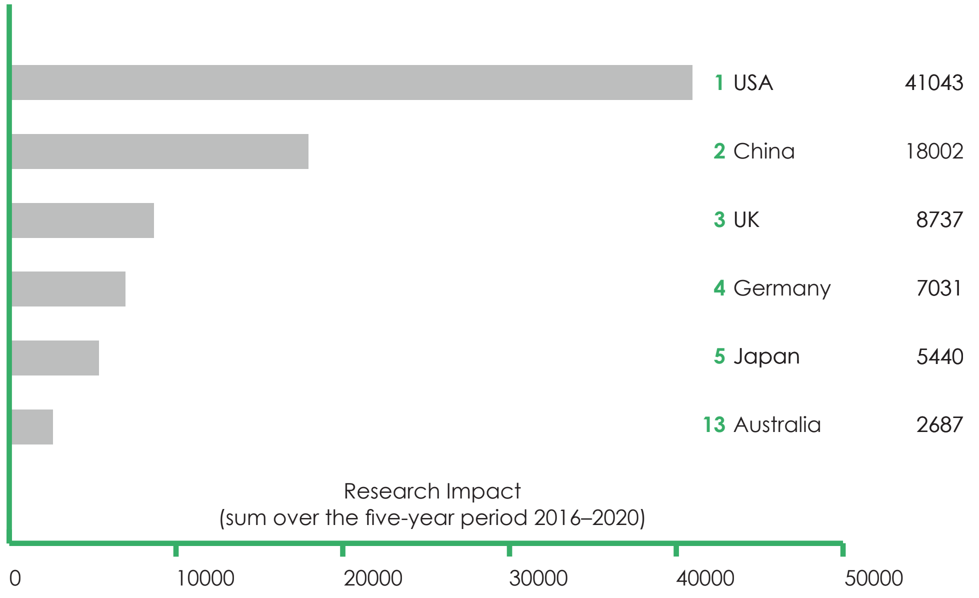
Australia is well positioned to take advantage of the opportunities arising from HPC, having already invested in significant computing infrastructure. Investing in large computing infrastructure carries security and investment risks. As an important national asset, HPC is subject to the threat of being physically compromised, which could result in immediate damage to national capability and reputation.

The cost of supercomputers is significant. Australia's Gadi—the world's 53rd most powerful supercomputer—required AUD$70 million of Australian government funding, and Japan's Fugaku—the world's fastest supercomputer—cost AUD$1.4 billion.

Supercomputers are also energy intensive; Gadi requires the same amount of electricity as that of a medium-sized suburb (though more energy efficient supercomputers are in development). Australia will need to consider how to best balance the opportunities afforded by HPC, while managing the large investment, cyber vulnerabilities and electricity costs. Careful management of the risks, such as utilising the opportunities provided by cloud-based supercomputing, may present Australia with yet more opportunity to expand our HPC toolset.

Research Impact (RI)

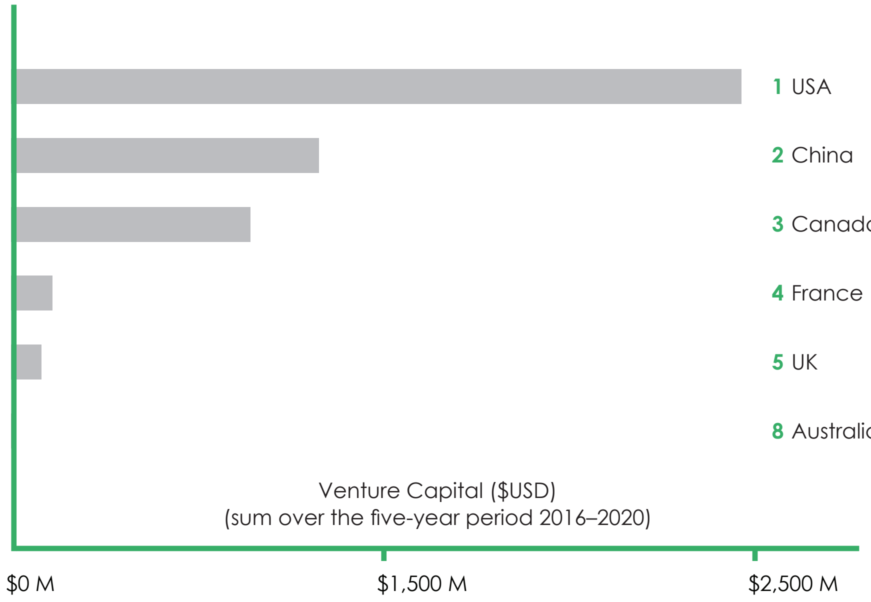
Australia ranks 13th for research impact in a field led by the United States and China. Total volume of published research has increased at around 7% p.a. over the 5 year period 2016–2020, with 24% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

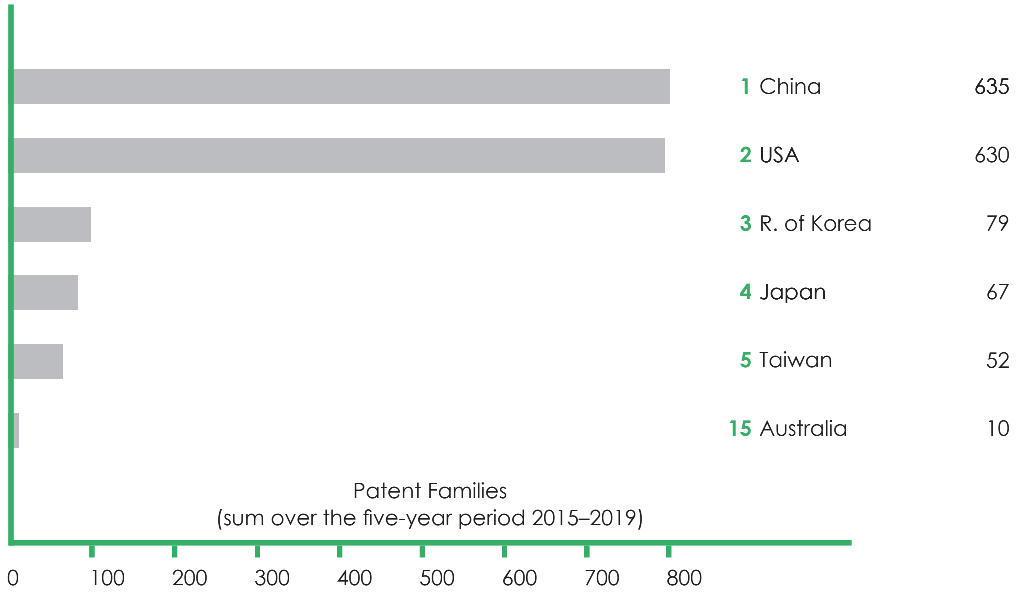
The United States leads venture capital (VC) investment in this area with more than double the amount invested by China; Australia is ranked 8th. Investment globally in this area has been growing at around 23% p.a. since 2016.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents - International

For this technology, most patents were filed by applicants or inventors in China and the United States. Australia ranks 15th. Overall patent applications have been increasing at around 1% annually since 2015.



Research Institutions - International

China and France are home to the top 3 institutions globally by research impact, with the United States filling out the top 10.

Rank	Top International Institution	Research Impact
1	Chinese Academy of Sciences | China	3543
2	French National Centre for Scientific Research (CNRS) | France	2944
3	Tsinghua University | China	2929
4	United States Department of Energy | United States	2351
5	IBM | United States	2333
6	University of Michigan, Ann Arbor | United States	2095
7	Oak Ridge National Laboratory | United States	2093
8	Argonne National Laboratory | United States	2070
9	Stanford University | United States	2034
10	Massachusetts Institute of Technology | United States	2030

Research Institutions - Australia

Within Australia, the University of Sydney has the highest research impact. No Australian institutions feature in the global top 50.

Rank	Top Australian Institution	Research Impact
1	University of Sydney	667
2	University of New South Wales	570
3	Royal Melbourne Institute of Technology	488
4	Australian National University	464
5	University of Melbourne	442
6	CSIRO	301
7	Monash University	297
8	University of Queensland	193
9	University of Western Australia	123
10	Curtin University	120

Patents - Australia

Top 4 Australian Patent Applicants	Patent Families
Anditi	1
Big Picture Medical	1
Big Picture Vision	1
Youranswer International	1

Patents filed by Australian businesses, 2015–2019.

Data current as at 16 March 2022.

Australian Government

CTPCO
CRITICAL TECHNOLOGIES POLICY COORDINATION OFFICE

Machine learning (incl. neural networks and deep learning)

Computer algorithms that automatically learn or improve using data and/or experience. Machine learning is a type of artificial intelligence. Applications for machine learning include computer vision, facial recognition, cybersecurity, media creation, virtual and augmented reality systems, media manipulation (e.g. deepfakes), content recommendation systems, and search engines

Key Sectors

Influences all sectors of the economy, including:

- Agriculture
- Banking & Finance
- Communications
- Defence & Defence Industry
- Energy & Environment
- Health
- Transport & Logistics
- Education & Research
- Mining & Resources
- Manufacturing
- Space

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security			X

Key Australian Government Actions

Initiatives

- Digital Economy Strategy
- Artificial Intelligence Action Plan
- Modern Manufacturing Strategy
- Research Package, Centre for Augmented Reasoning at the University of Adelaide
- Next Generation Technologies Fund
- Office of Future Transport Technology – National Policy Framework for Land Transport Technology and Action Plan
- Automotive Engineering Graduate Program
- Cooperative Research Centre Projects
- AI Future Science Platform

Regulations

- Defence and Strategic Goods List 2021

Example Outcomes

- More productive knowledge industries
- Fast, reliable and accurate computer vision
- Improved farm productivity, reduced reliance on chemical usage, and reduced wastage
- Improved patient outcomes from more targeted medical interventions and prescribing
- More efficient healthcare spending by reducing unnecessary treatments
- Lower rates of offending by people on bail or parole
- Less downtime for critical infrastructure from better predictive maintenance
- Reduced commute times through better traffic management
- More satisfied consumers through better product and content recommendations
- Better child development outcomes by more accurately predicting which children or families may require additional support
- Widespread application of artificial intelligence tools
- More efficient manufacturing processes

Underpinning Science

ANZ Standard Research Classification Category

- Artificial Intelligence
- Computer vision and multimedia computation
- Cybersecurity and privacy
- Data management and data science
- Graphics, augmented reality and games
- Human-centred computing
- Machine learning
- Software engineering
- Pure mathematics
- Statistics

Example Applications

Readiness Level – Now

- Product and content recommendation systems
- Fraud detection
- Creating highly realistic deepfakes and synthetic media
- Spam filtering
- Detecting potential malware or cyber intrusions
- Detecting harmful or unlawful content
- Public transport planning
- Precision agriculture
- Predictive and smart policing algorithms

Readiness Level – 2–5 years

- Computer vision for autonomous vehicles
- Reliably detecting deepfakes and synthetic media
- High-resolution weather models
- Creating high quality synthetic datasets to train other machine learning models
- Creation of voice and computer generated actors and scenes

Readiness Level – Beyond 5 years

- Fully autonomous systems – driverless vehicles and drones
- Personalised medicine
- Responding to novel cyber-attacks
- Creation of novel pharmaceuticals
- Personal assistant and companion robots

Australia's place in the world

Australia ranks 9th globally for research impact, led by the University of Melbourne. The United States dominates research on machine learning, and also has the top five international institutions. Overall publications have increasing at 22% p.a.

Australia ranks 13th for venture capital (VC) investment, which is led by the United States and China. VC investment for machine learning has been increasing at 18% p.a. since 2016. Patents have been increasing at 59% p.a. since 2015, led by China, ahead of the United States, with Australia in 17th.

Opportunities and Risks

Machine learning has significant potential to affect Australia's economic prosperity and Australia's national security.

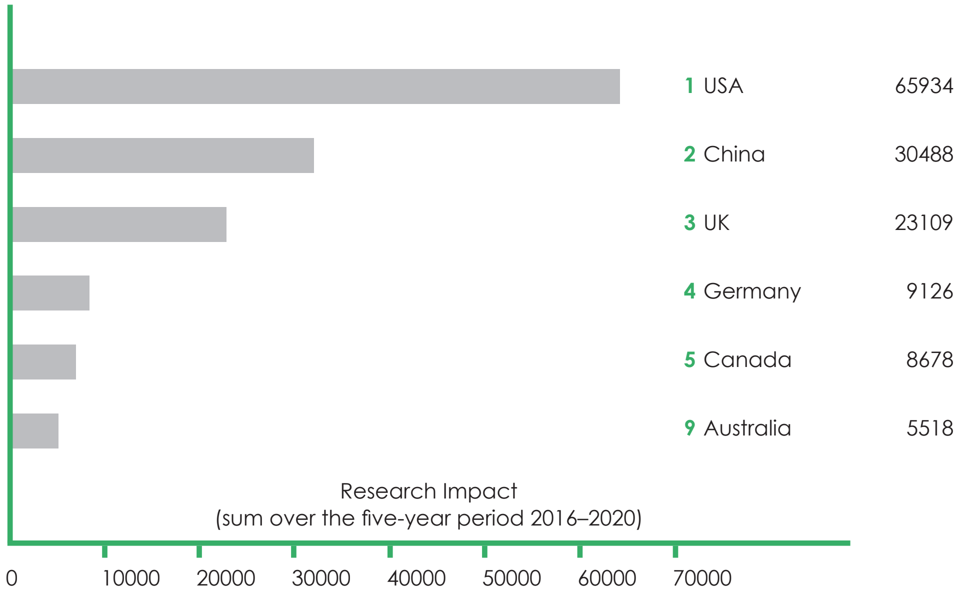
Opportunities for machine learning focus on increasing productivity and making artificial intelligence use cases more independent, practical and economical. Machine learning can automate or streamline many monotonous, time-consuming or low-value activities, freeing people to focus on more valuable or less unpleasant tasks. It has been estimated that up to 46% of jobs may be automated through automation and existing workers will be financially better off by between $4,000 to $15,000 p.a. by 2030.

Some of the key risks from machine learning are changing workforce requirements, poorly designed use cases, overly-optimistic reliance on machine learning-based tools, and intentional use of machine learning-based tools to undermine Australia's national interest. Falling costs may mean that businesses automate some roles and reduce staffing levels; this has the potential to create new and different opportunities for the workforce. Machine learning to automate processes and functions is not a one-size-fits-all solution and there are risks associated with applying the technology to situations before it is ready or without managing limitations during development and implementation. These risks range from lost money or opportunities, up to and including physical harm to people and property.

Machine learning also has the potential to underpin new cyber or physical weapons that could be used by or against Australia. To combat this, awareness and technical understanding of machine learning technology will be vital.

Research Impact (RI)

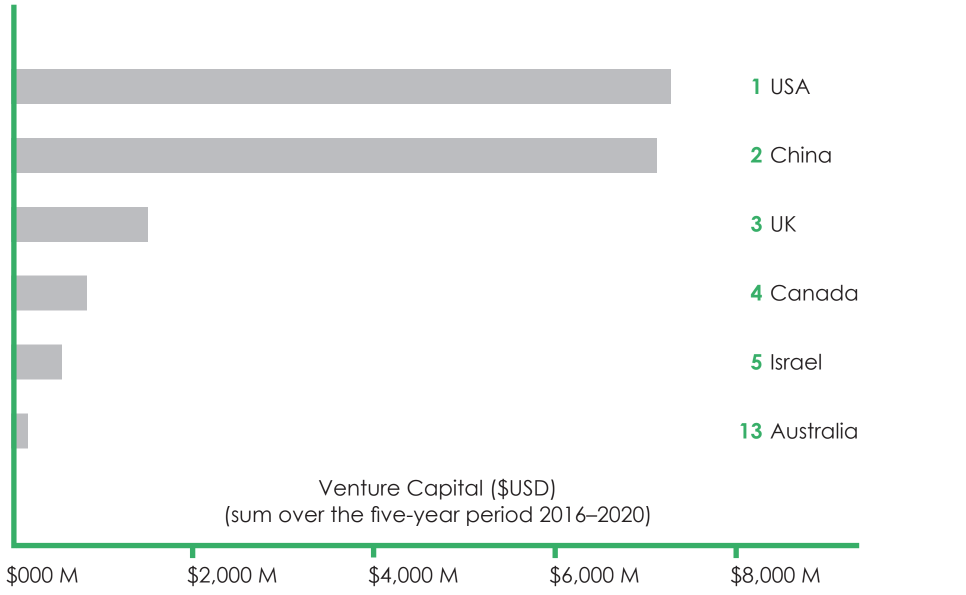
The United States has the highest research impact in this field, with Australia ranked 9th globally. Total volume of published research has increased at around 22% p.a. over the 5 year period 2016–2020, with 21% of all research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources and facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

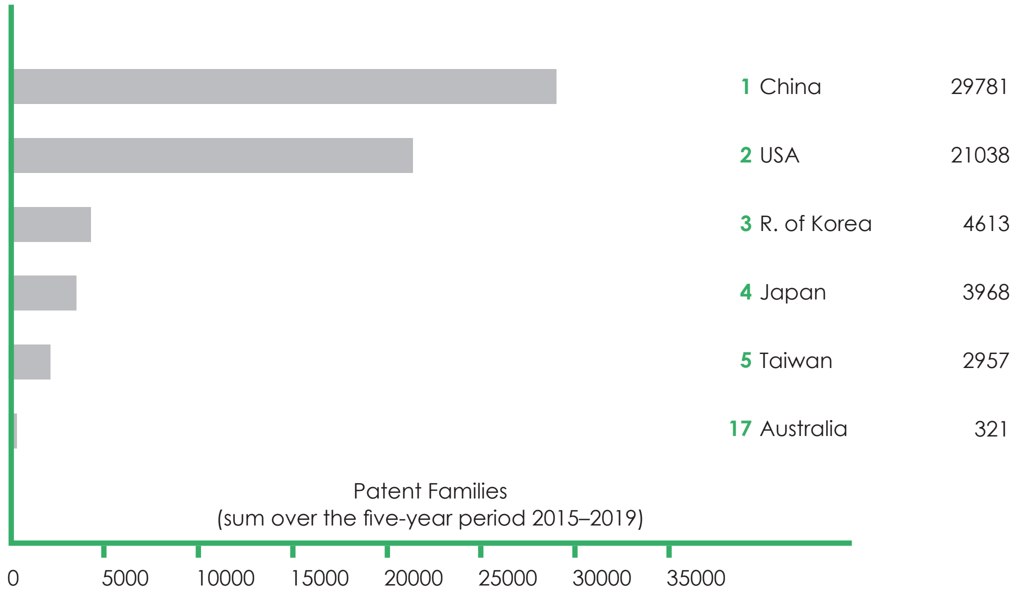
Australia ranks 14th for venture capital (VC) investment in machine learning, with the United States (1st) and China (2nd) leading VC investment ahead of the United Kingdom, Canada and Israel. Investment in this area has been growing at 18% p.a. since 2016.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

Most patents for this technology were filed by Chinese applicants or inventors, ahead of the United States. Australia ranks 17th. Global patent applications have been increasing at 59% annually since 2015.



Research Institutions – International

The United States has the top five international institutions, with Alphabet Inc. (a.k.a. Google) having the highest research impact. The rest of the top 10 institutions are from the United Kingdom (3) and China (2).

Rank	Top International Institution	Research Impact
1	Alphabet Inc. | United States	10284
2	Stanford University | United States	5929
3	Massachusetts Institute of Technology | United States	4534
4	University of Washington | United States	4398
5	Harvard University | United States	4167
6	University of Oxford | United Kingdom	2974
7	Imperial College London | United Kingdom	2893
8	Chinese Academy of Sciences | China	2672
9	University College London | United Kingdom	2567
10	Tsinghua University | China	2507

Research Australian – Australia

Within Australia, the University of Melbourne and the University of Technology Sydney have the highest research impact.
There are no Australian institutes in the top 50 international institutions.

Rank	Top Australian Institution	Research Impact
1	University of Melbourne	590
2	University of Technology Sydney	563
3	Deakin University	497
4	University of Sydney	371
5	University of Adelaide	354
6	Monash University	324
7	CSIRO	288
8	University of New South Wales	284
9	University of Queensland	274
10	Macquarie University	184

Patents – Australia

Top 5 Australian Patent Applicants	Patent Families
Atlassian	9
CSIRO	4
n/a (private citizen applicants only)	3
University of Melbourne	2
Swinburne University of Technology	2

Patents filed by Australian businesses, 2015–2019.

Natural language processing (incl. speech and text recognition and analysis)

Systems that enable computers to recognise, understand and use written and/or spoken language in the same ways that people use language to communicate with each other. Natural language processing is a type of artificial intelligence. Applications for natural language processing include predictive text, language translation, virtual assistants and chat bots, summarising long documents and making technologies more accessible and inclusive.

Key Sectors

Influences all sectors of the economy, including:

- Agriculture
- Banking & Finance
- Communications
- Defence & Defence Industry
- Health
- Education & Research
- Transport & Logistics
- Intelligence
- Law enforcement
- Manufacturing

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security			X

Key Australian Government Actions

Initiatives

- Artificial Intelligence Action Plan
- AI-focused Cooperative Research Centre Projects
- Digital Economy Strategy
- Next Generation Technologies Fund & Defence Innovation Hub

Regulations

- Defence and Strategic Goods List 2021

Example Outcomes

- Technology that is more accessible and inclusive.
- Faster, more intuitive access to information.
- More productive use of existing corporate, government and academic information.
- Faster, more equitable access to government services.
- Increased capacity for online and remote learning solutions.
- More natural human-machine teaming.
- Fewer language barriers.
- More accessible and inclusive society.
- More local and special interest news publishing.
- Increased access to counselling and machine-driven psychological support services.
- More timely regulation and compliance monitoring.

Underpinning Science

ANZ Standard Research Classification Category

- Artificial Intelligence
- Computer vision and multimedia computation
- Data management and data science
- Graphics, augmented reality and games
- Human-centred computing
- Machine learning
- Software engineering
- Pure Mathematics
- Statistics
- Linguistics

Example Applications

Readiness Level – Now

- Text-to-speech translation in multiple languages and vice-versa
- Multiple language translation in multiple forms of media
- Writing news articles for simple, structured events (finances, sports, weather)
- Increased cognition for search engine queries
- Sentiment analysis for news and speech media
- Simple chatbots and digital assistants like Alexa/Google Home
- Low-code application development using simple language to code translation
- Monitoring social media for signs of suicidal ideation
- Identifying signs of mental illness from everyday speech and writing

Readiness Level – 2–5 years

- Text summarisation and concept identification
- Cross-language search engines
- Regulatory design and compliance monitoring (RegTech)
- Complex, creative and unique content creation from small snippets of media
- Digital assistants, chatbots and search engines that can understand and respond to increasingly complicated queries
- Create lyrics for music that match a given theme/beat/tune

Readiness Level – Beyond 5 years

- Real-time idiomatic language machine translation
- Personalised virtual assistants – can create media such as text or speech in your style/voice
- Create a synthetic language
- Comprehend, analyse and report on huge datasets consisting of multiple media sources
- Thought to text/speech conversion and vice versa including privacy filters

Australia's place in the world

The United States, led by Alphabet Inc (aka Google), has the highest research impact in this field; China ranks second and Australia 8th. Among Australian institutions, the University of Technology Sydney, followed closely by the University of Sydney, have the highest research impact for natural language processing (NLP); both are also in the top 50 internationally. Global venture capital (VC) investment in NLP is concentrated in China and the United States. Patents in this area have been growing at around 39% p.a. since 2015, with the United States and China well ahead in patent numbers.

Australia's research strength in this area, coupled with strengths in related technologies (including machine learning and AI algorithms), and strong international partnerships, means we are well positioned to take advantage of NLP's opportunities.

Opportunities and Risks

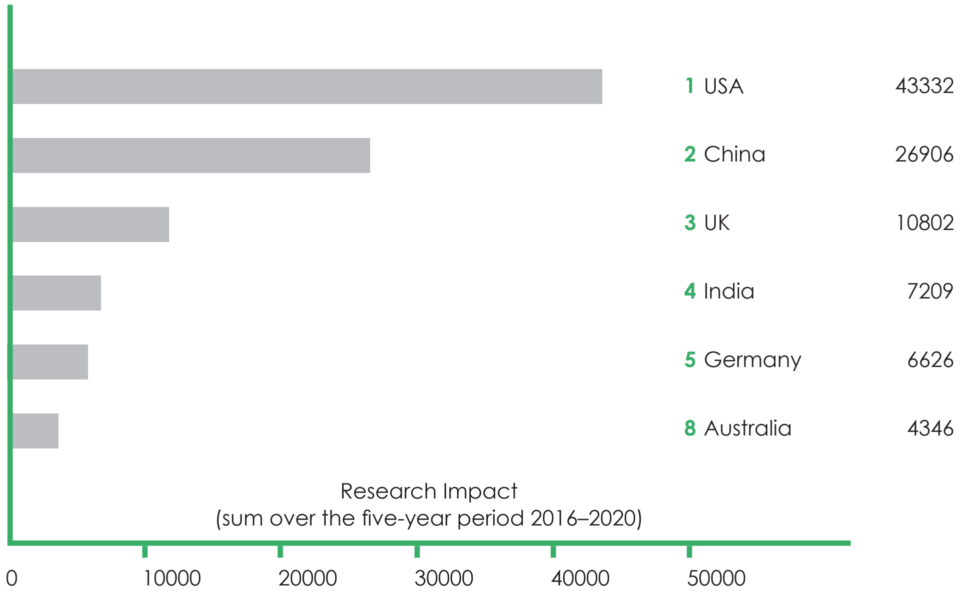
For decades, people have conformed to the limited and often unintuitive ways of computers. Natural language processing (NLP) turns this process around by enabling computers to 'understand' how humans naturally communicate and use information.

NLP can make workers more productive by easing their interactions with machines, reducing the time taken to find and analyse information, and automating simple or repetitive tasks. NLP can also improve Australia's national security by supporting law enforcement and intelligence professionals in identifying relevant information amidst the unprecedented volume of new content that people create every day. NLP may also make Australia more inclusive by enabling more people to communicate using their preferred language and by making technology more like talking or writing.

NLP also presents risks for Australia. Poorly designed NLP-based bots, text generation or analysis tools can perpetuate harmful biases or stereotypes, or exclude people from participating equally in society. NLP has potentially malicious applications, including enabling small teams of people to mount sophisticated and widespread disinformation campaigns, and creating software that can reliably impersonate the writing style, quirks and mannerisms of well-known authors and public figures.

Research Impact (RI)

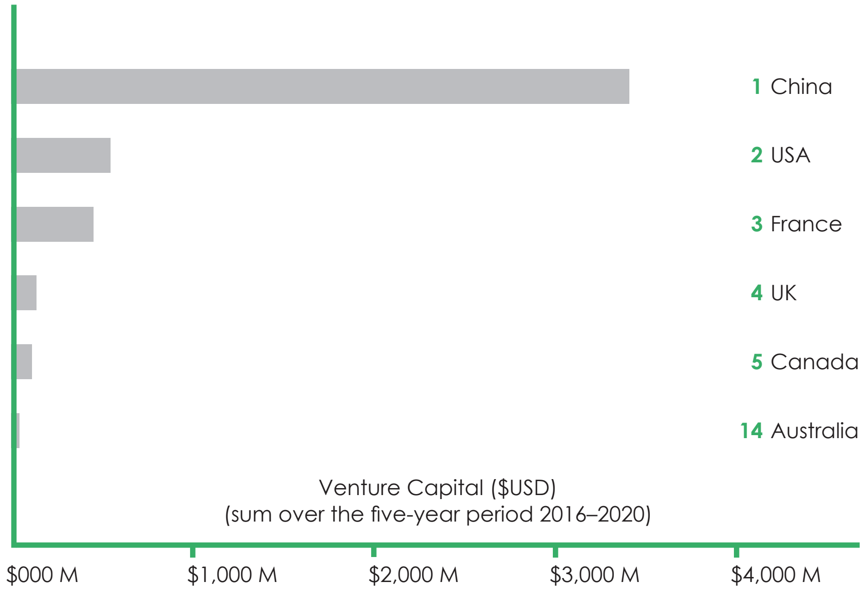
The United States leads research impact, with Australia ranked 8th globally. Total volume of published research has increased at around 19% p.a. over the 5 year period 2016–2020, with 19% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality

VC Investment

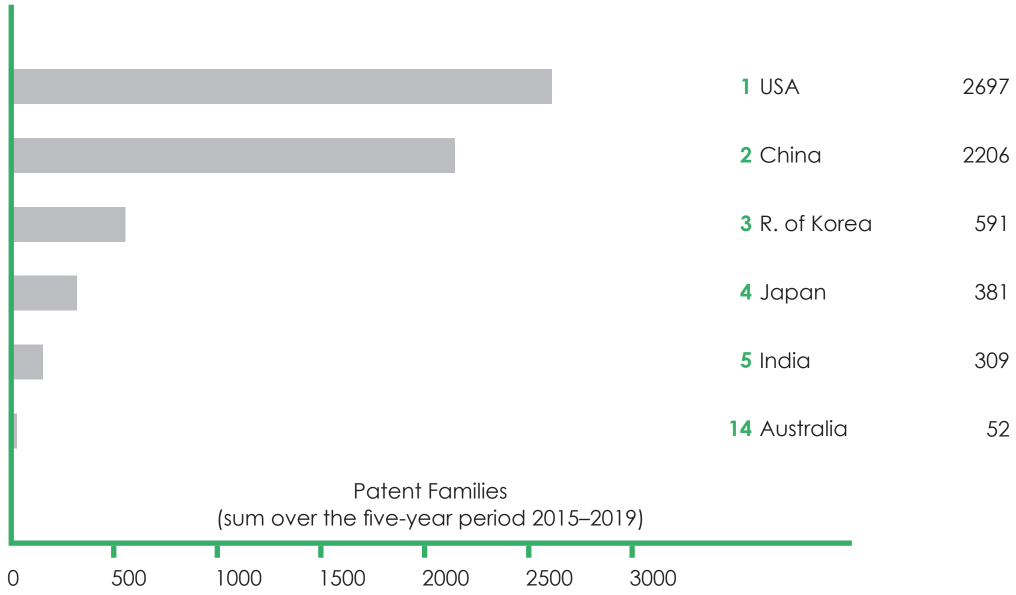
Australia is ranked 24th globally for relative venture capital (VC) investment, which is led by China. Investment in this area has been slowing since 2016.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

The number of patents filed annually in this field has increased by 39% from 2015 to 2019. Most patents for this technology were filed by applicants or inventors from the United States and China, and Australia ranks 14th.



Research Institutions – International

The United States has 7 institutes in the top 10 international institutions. Alphabet Inc (aka Google) is the top ranked institute.

Rank	Top International Institution	Research Impact
1	Alphabet Inc. | United States	4300
2	Stanford University | United States	4275
3	Chinese Academy of Sciences | China	4139
4	Harvard University | United States	3558
5	Microsoft USA | United States	2137
6	Massachusetts Institute of Technology | United States	1949
7	University of Washington | United States	1928
8	National Institutes of Health | United States	1926
9	Nanyang Technological University | Singapore	1867
10	University College London | United Kingdom	1816

Research Australian – Australia

Within Australia, the University of Technology Sydney has the highest research impact, which places it 39th internationally. The University of Sydney is ranked 48th internationally.

Rank	Top Australian Institution	Research Impact
1	University of Technology Sydney	819
2	University of Sydney	688
3	University of Adelaide	370
4	University of Melbourne	367
5	University of Western Australia	335
6	University of New South Wales	299
7	CSIRO	248
8	Monash University	240
9	University of Queensland	203
10	Australian National University	150

Patents – Australia

Eleven Australian companies have each filed one patent family in this field. Five of these are included in the table below.

Top 5 Australian Patent Applicants	Patent Families
Atlassian	1
Vendome Consulting	1
Cochlear	1
The Utree Group	1
Safesoft	1

Patents filed by Australian businesses, 2015–2019.

Protective Cyber Security Technologies

Systems, algorithms and hardware that are designed to enable a cyber security benefit. Applications for cyber security technologies include but are not limited to; operational technology security, trust and authentication infrastructures, protection of aggregated data sets, protection of AI systems and supply chain security.

Key Sectors

Influences all sectors of the economy, including:

- Agriculture
- Banking & Finance
- Communications
- Defence & Defence Industry
- Energy & Environment
- Health
- Transport & Logistics
- Education and Research
- Mining and Resources
- Manufacturing
- Space

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security			X

Key Australian Government Actions

Initiatives

- Australia's Cyber Security Strategy 2020
- Australian Cyber Security Centre
- Australia's Cyber and Critical Tech Cooperation Program
- International Cyber and Critical Technology Engagement Strategy
- Cyber Security Cooperative Research Centre
- Australian Cyber Security Growth Network
- Australian Information Security Evaluation Program
- Digital Economy Strategy

Regulations

- Defence and Strategic Goods List 2021

Example Outcomes

- More automation and less human involvement in routine cybersecurity activities
- Proactive identification of, and response to, cybersecurity threats
- Doing business online is no less secure than doing business offline
- Secure smart cities
- Secure smart grids
- Secure and privacy preserving use of government data holdings
- Secure IoT and home automation
- Sovereign cyber security capabilities
- Availability of low-cost, high-efficacy secure by design principles and tools
- Reduced downtime due to cybersecurity incidents
- More secure use of shared computer infrastructure

Underpinning Science

ANZ Standard Research Classification Category

- Communications Engineering
- Artificial intelligence
- Cybersecurity and privacy
- Data management and data science
- Distributed computing and systems software
- Machine learning

Example Applications

Readiness Level – Now

- Automated detection of potential indicators of malicious cyber activity
- Data loss prevention
- End-to-end encryption
- Hardware security module, ubiquitous hardware authentication and secure hardware root trust
- Network diodes
- Additional multifactor authentication methods, including passwordless, biometric and ubiquitous hardware authentication
- Security Information and Event Management (SIEM)
- Virtual private networks (VPNs)

Readiness Level – 2–5 years

- AI-assisted tools for secure software design
- AI-assisted software security auditing tools
- Content Disarm & Reconstruction (CDR)
- Network detection and response (NDR) technology
- Sovereign cloud
- Zero trust network access (ZTNA)
- Secure multi-level terminal (Cross Domain Desktop Compositor) for secure information sharing across domains

Readiness Level – Beyond 5 years

- Automated detection and response to novel cyber threats
- Autonomous cyber security for low power and resource-constrained devices, such as connected health devices
- Format-preserving encryption
- Homomorphic encryption

Australia's place in the world

The United States leads public research in this field well ahead of China, the United Kingdom and Australia. Although Australia's research does rank in the top 5 globally, at 4th. Swinburne University of Technology is Australia's leading institution by research impact, ranking 11th worldwide. These rankings should be treated cautiously as different research and publication practices in this field (particularly a greater preference for informal publication methods) mean the underlying data is likely incomplete.

Australia is ranked 8th for venture capital (VC) investment, well behind the investment levels of the United States. China and the United States have the highest number of patents in this field, with Australia is ranked 20th.

Opportunities and Risks

Australians depend on cybersecurity technologies to protect the digital and connected devices and systems that underpin Australia's economy and security.

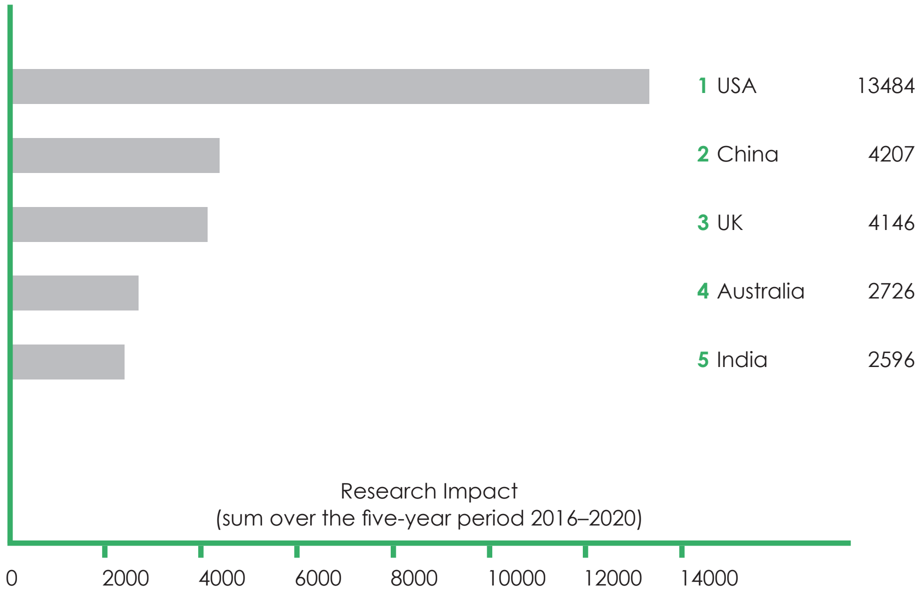
Opportunities for Australia from advances in protective cyber security technologies include exporting cybersecurity goods and services to the world, increasing business and consumer confidence and uptake of cyber-enabled technologies, and reducing the costs of combatting and responding to malicious cyber activities.

Advances in protective cyber security technologies also pose risks for Australia. Malicious actors can benefit from protective cyber security technologies by using those technologies to conceal their unlawful activities and increase the costs of detection and response.

Risks for Australia from not keeping pace with global advances in protective cyber security technologies include increased theft or destruction of personal and commercially sensitive digital information, less reliable critical infrastructure and government services, increased spending on cyber security imports and services, and decreased confidence in Australia's digital economy.

Research Impact (RI)

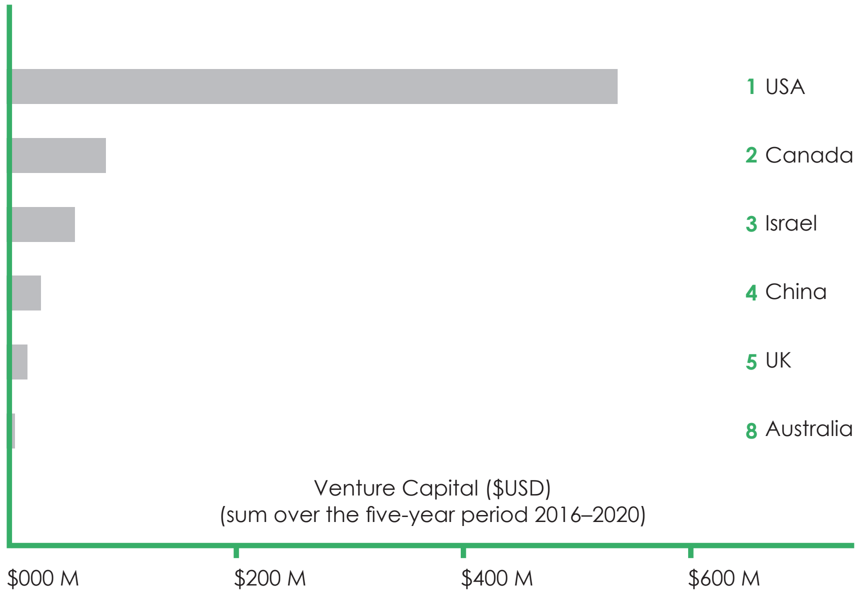
Australia ranks 4th for research impact, with the United States having the highest research impact. The total volume of research publications has been increasing at 18% p.a. over the 5 year period 2016–2020, with 18% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

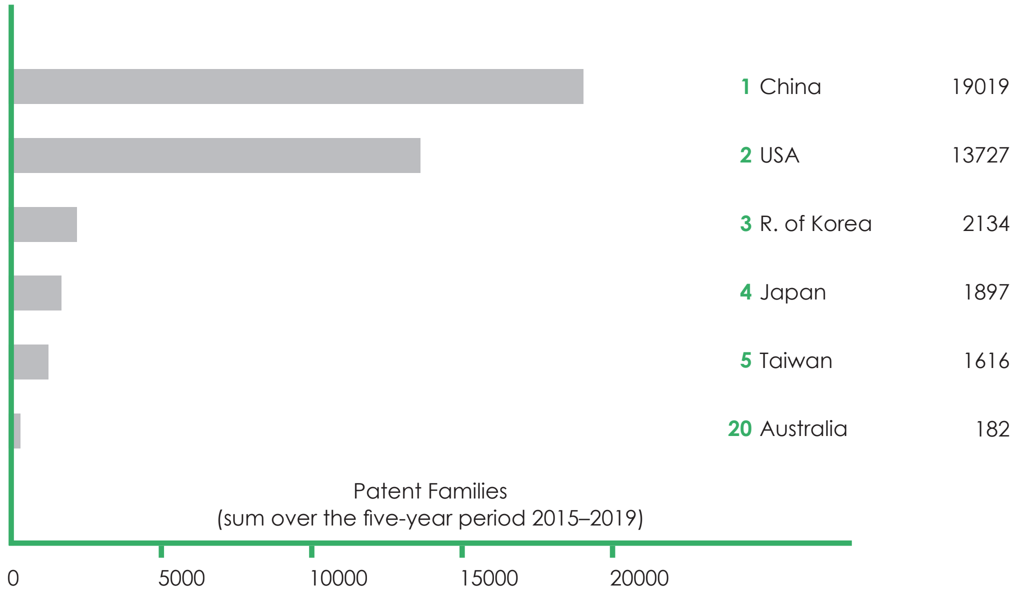
The United States has significantly higher venture capital investment (VC) in this area, well above that of Canada and Israel. Australia is ranked 8th for VC investment. Since 2016, VC investment has been decreasing at around 5% p.a.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

The highest number of patents for this technology were filed by applicants or inventors from China and the United States. Overall patent applications have been increasing at 6% annually since 2015. Australia is ranked 20th.



Research Institutions – International

The United States has 6 institutes in the top 10 international institutions for research impact.

Rank	Top International Institution	Research Impact
1	Johns Hopkins University | United States	666
2	George Mason University | United States	545
3	Virginia Polytechnic Institute and State University | United States	466
4	Singapore University of Technology and Design | Singapore	452
5	Pace University | United States	422
6	Tsinghua University | China	402
7	Norwegian University of Science and Technology | Norway	390
8	Amrita Vishwa Vidyapeetham | India	387
9	Florida International University | United States	348
10	Massachusetts Institute of Technology | United States	342

Research Australian – Australia

Based on the publically available information, within Australia, Swinburne University of Technology has the highest research impact nationally, and is ranked 11th internationally. The top 4 Australian institutions are ranked in the top 50 internationally.

Rank	Top Australian Institution	Research Impact
1	Swinburne University of Technology	337
2	Charles Darwin University	270
3	University of Technology Sydney	257
4	Defence Science & Technology Group	167
5	University of Melbourne	166
6	Deakin University	164
7	Macquarie University	157
8	University of New South Wales	154
9	Edith Cowan University	148
10	Queensland University of Technology	126

Patents – Australia

Top 5 Australian Patent Applicants	Patent Families
New South Innovations	3
Introspectus	3
Atlassian	3
CSIRO	2
Aristocrat Technologies Australia	2

Patents filed by Australian businesses, 2015–2019.

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 nutritious or require less water or pesticides, treating genetic diseases by replacing faulty genes with working copies, and cell therapies that treat diseases by extracting, modifying and reimplanting patients' own cells.

Key Sectors

- Health
- Agriculture
- Environment
- Defence & Defence Industry
- Education & Research

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security		X	

Key Australian Government Actions

Initiatives

- Medical Research Future Fund (MRFF) Priority Mission
- National Health Genomics Policy Framework 2018-2021
- National Microbial Genomics Framework 2019-2022
- National Manufacturing Strategy – Priority area of Medical Products
- National Research Infrastructure (NRI) and 2021 NRI Roadmap
- Agriculture Innovation Policy Statement
- Various Rural RDC priority initiatives

Regulations

- Gene Technology Act 2000
- Gene Technology Regulations 2001
- Research Involving Human Embryos Act 2002
- Defence and Strategic Goods List 2021

Example Outcomes

- Pandemic preparedness and response
- Improved individual health
- Improved public health outcomes and medical care
- Better control of invasive species
- Sustainable agriculture through crops and animals that are more disease or stress resistant, or have improved yields
- Discovery of therapeutic targets and novel therapeutics approaches
- Improved food security through crops and animals suited to more variable climates
- Provision of therapeutic and food aid
- Trade and consumer assurance through traceability and authenticity of animals and food

Opportunities and Risks

Genetic engineering forms the foundation for synthetic biology (the application of engineering principles with genetic components to create new biological products or systems) and has the potential to dramatically improve our agricultural outputs and lead to advances in healthcare and treatment of chronic and debilitating conditions. Challenges remain around establishing appropriate regulatory regimes and the social licence for gene modification, social acceptance of sharing of genetic information, and adequate data infrastructure and governance. The history of public interactions with genetically modified organisms shows there is a real risk of having insufficient social licence and acceptance of genetic modification, resulting in poor uptake, a lack of return on investment and overall lost opportunities.

For genetically engineered crops and animals there is uncertainty around how to adequately assess and manage unexpected downstream ramifications of, for example, longer-lived plants or animals, or those with slower reproductive cycles, or the impact of engineered crops in the natural. There is also potential for the misuse and diversion of genetic engineering and associated technologies to create biological threats, such us untreatable bacteria and viruses.

Whilst genetic engineering has the potential to overcome diseases and debilitating conditions, there is also the potential to use this technology to introduce desirable traits and create "designer babies". Australia, in collaboration with the United Kingdom, has been instrumental in developing the Ethical Principles for Human Augmentation Technologies, which are intended to establish a set of principles for best practice design, development genetic engineering technologies.

Many of the risks associated with genetic engineering can be overcome through ongoing social engagement between researchers, industry, government and the public, and by ensuring robust standards and regulatory frameworks that promote access, whilst recognising and managing the associated risks.

Underpinning Science

ANZ Standard Research Classification Category

- Agricultural biotechnology
- Animal production
- Applied computing
- Applied ethics
- Artificial intelligence
- Biochemistry and cell biology
- Bioinformatics and computational biology
- Crop and pasture production
- Data management and data science
- Fisheries sciences
- Forestry sciences
- Genetics
- Horticultural production
- Immunology
- Industrial biotechnology
- Machine learning
- Medical biotechnology
- Sociology
- Plant biology
- Statistics
- Veterinary sciences

Australia's place in the world

While the research landscape is dominated by the USA and China, Australia is ranked 11th for research impact, led by the University of Melbourne. China has significantly more patents in the area, with almost double that of the United States.

The United States dominates venture capital (VC) investment in this area, dwarfing VC investment of the other top 5 countries: China, the Netherlands, Denmark and Japan. Australia is unranked for VC investment.

Australia has well-established research and development capability in genetic engineering. The CSIRO has led development of genetically modified cotton, which accounts for nearly all the cotton varieties in Australia, contributing to a $1.5 billion p.a. export market.

Australia has also developed several world first vaccines using genetic engineering, including the human papilloma virus (HPV) vaccine, Gardasil, and the Hendra vaccine for horses. Australian research involving genetic engineering and modification contributed to the development of COVID19 vaccines.

Example Applications

Readiness Level – Now

- Vaccine development
- Communicable diseases management (i.e. monitoring, tracing and response)
- Mitochondrial donation
- Livestock enhancement for improved productivity or commercial features
- Cell therapies for improved disease treatment (e.g. stem cell treatments)
- Genetic manipulation that introduces or removes genetic traits (e.g. for resistance, yield, performance, etc.)
- Food and animal traceability – authenticity and contamination detection
- CRISPR-Cas9 gene editing

Readiness Level – 2–5 years

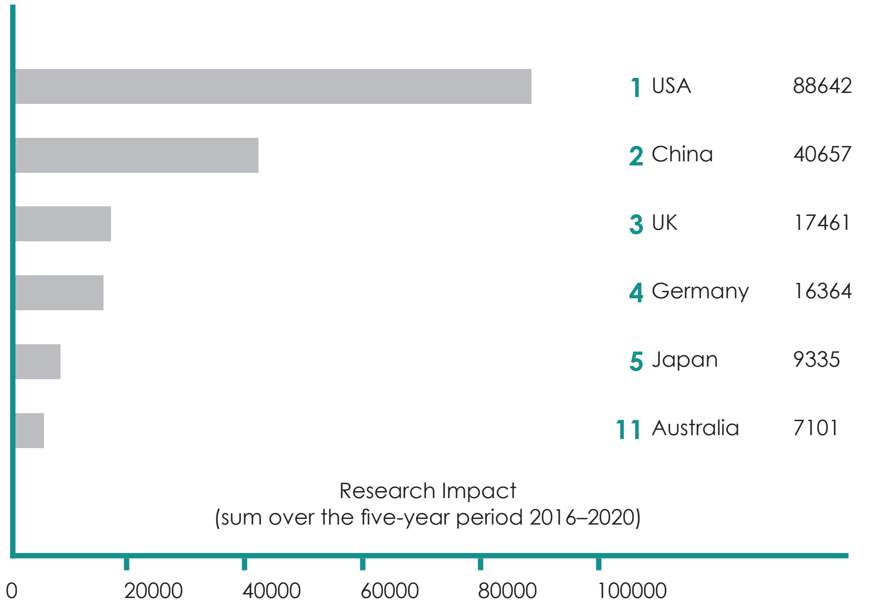
- Health risk prediction, early intervention and targeted treatments
- Improved and more diverse cell therapies for improved disease treatment (stem cell treatments)
- Synthetic biology and downstream applications, e.g. alternative protein sources and precision fermentation techniques.
- Conservation – biodiversity and removal of pest species
- Designer biology (i.e. development of designer plants, animals, foods, bacteria)

Readiness Level – Beyond 5 years

- Expanded intervention and targeted treatments for genetic disorders
- Genetic modification of humans to introduce or remove genetic traits (e.g. disease, performance)
- Expanded synthetic biology applications, e.g. biofoundries and biomaterials

Research Impact (RI)

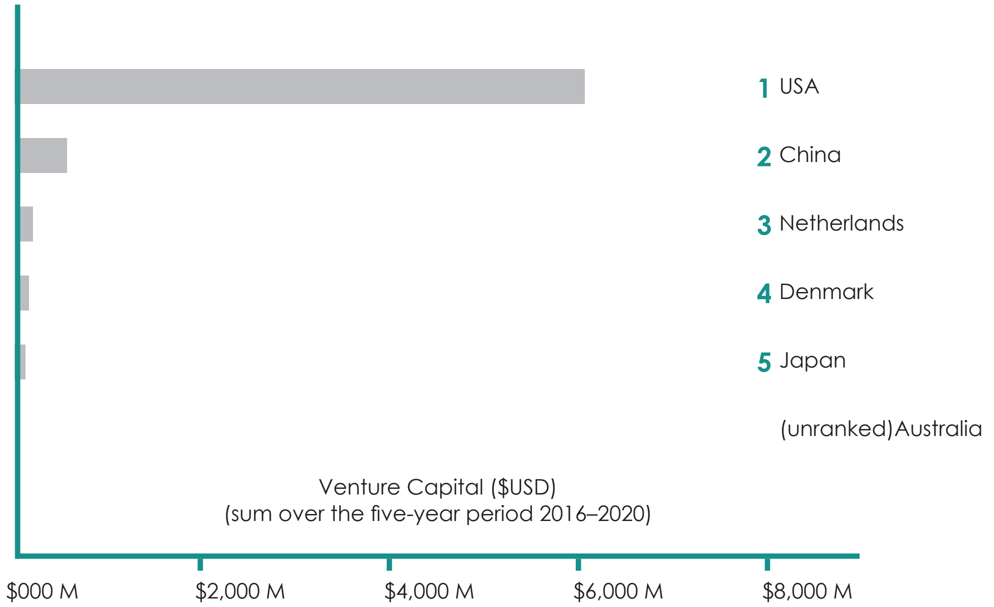
Australia is ranked 11th for research impact internationally, which is led by the United States. Total volume of published research has increased at around 3% p.a. over the 5 year period 2016–2020, with 26% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

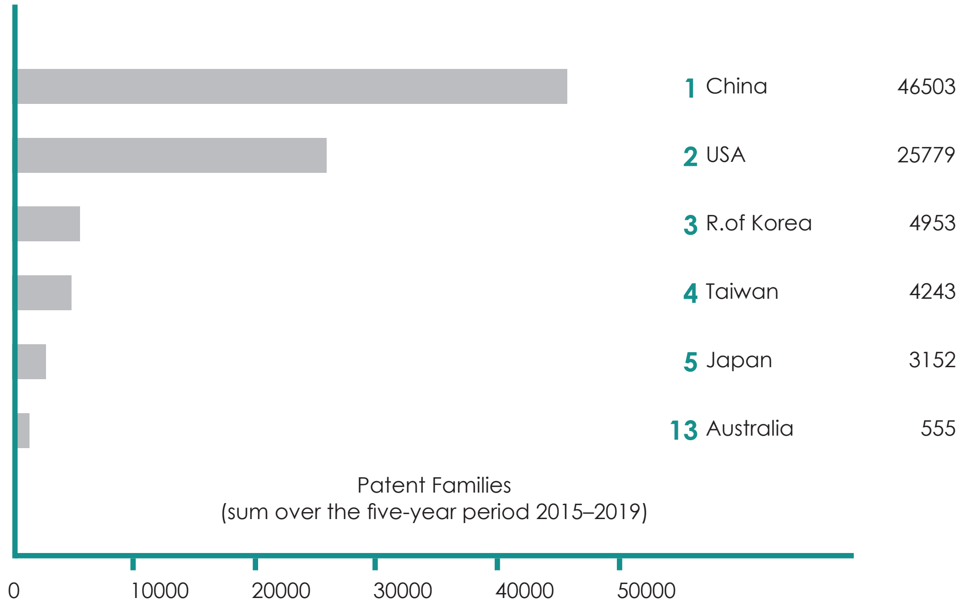
Australia is unranked venture capital (VC) investment for genetic engineering, which is dominated by the United States. Since 2016, investment has increased about 62% p.a.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

The number of patents filed annually in this field has increased by 7% from 2015 to 2019. Most patents for this technology were filed by Chinese applicants or inventors, almost double that of the United States. Australia ranks 13th.



Research Institutions – International

The United States has 8 of the top 10 international institutions, with China and France filling the remaining positions.

Rank	Top International Institution	Research Impact
1	Harvard University | United States	12455
2	Massachusetts Institute of Technology | United States	11886
3	Chinese Academy of Sciences | China	9390
4	Howard Hughes Medical Institute | United States	9152
5	Broad Institute | United States	6527
6	University of California at Berkeley | United States	6303
7	National Institutes of Health | United States	5832
8	Stanford University | United States	4839
9	French National Centre for Scientific Research (CNRS) | France	4813
10	University of Pennsylvania | United States	4078

Research Institutions – Australia

Within Australia, the University of Melbourne leads for research impact, ahead of the University of Queensland. There are no Australian institutes in the top 50 international institutions.

Rank	Top Australian Institution	Research Impact
1	University of Melbourne	1556
2	University of Queensland	1428
3	University of Sydney	793
4	CSIRO	780
5	Monash University	733
6	University of Western Australia	476
7	University of Adelaide	475
8	University of New South Wales	468
9	Queensland University of Technology	455
10	Australian National University	342

Patents – Australia

Top 5 Australian Patent Applicants	Patent Families
CSIRO	31
The Council of the Queensland Institute of Medical Research	22
Queensland University	17
University of Sydney	17
New South Innovations	12

Patents filed by Australian businesses, 2015–2019.

Australian Government

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Genome and genetic sequencing and analysis

Tools and techniques for quickly sequencing (i.e. 'reading') the genetic material of human beings, other living organisms and viruses, and for analysing and understanding the functions of those sequences. Applications for genomics and genetic sequencing and analysis include identifying the genes associated with particular diseases or biological functions, identifying new communicable diseases, crop and livestock breeding and predicting how effective drugs will be for different patients.

Key Australian Government Actions

Initiatives

- Medical Research Future Fund (MRFF) Priority Mission
- National Health Genomics Policy Framework 2018–2021
- National Manufacturing Strategy – Priority area of medical products
- National Collaborative Research Infrastructure Strategy
- Agricultural Innovation Policy Statement
- Various Rural RDC priority initiatives
- Biomedical Translation Fund

Regulations

- Privacy Act 1988 (Cwth) – section 6FA(d) health information
- National Association of Testing Authorities standards for laboratory testing and analysis, and standard ISO15189.
- Therapeutic Goods Act 1989 (Cth)
- Therapeutic Goods (Medical Devices) Regulations 2002
- Defence and Strategic Goods List 2021

Example Outcomes

- Pandemic preparedness and responsiveness
- Improved public health outcomes and medical care
- Improved population health screening and planning
- Sustainable agriculture – increasing yields from plants and animals while improving their disease and stress-resistance
- Discovery of therapeutic targets and novel therapeutics approaches
- Improved food security (in response to climate change)
- Provision of therapeutic and food aid
- Trade and consumer assurance through traceability and authenticity of animals and food
- Better control of invasive species
- Improved environmental monitoring

Underpinning Science

ANZ Standard Research Classification Category

- Agricultural biotechnology
- Animal production
- Applied computing
- Applied Ethics
- Artificial Intelligence
- Biochemistry and cell biology
- Bioinformatics and computational biology
- Clinical sciences
- Crop and pasture production
- Data management and data science
- Fisheries sciences
- Forestry sciences
- Genetics
- Horticultural production
- Immunology
- Industrial biotechnology
- Machine learning
- Medical biotechnology
- Sociology
- Plant biology
- Software engineering
- Statistics
- Veterinary sciences

Example Applications

Readiness Level – Now

- Vaccine development
- Communicable diseases management – monitoring, tracing and response
- Cell therapies for improved disease treatment (such as stem cell treatments)
- Improved diagnostic and therapeutic targeting capability
- Livestock selection or enhancement for improved productivity or commercial features
- Genetic manipulation that introduces or removes genetic traits (e.g. yield or resistance)
- Food and animal traceability – authenticity and contamination detection
- Conservation – biodiversity, removal of pest species

Readiness Level – 2–5 years

- Synthetic biology and downstream applications, such as alternative protein sources and precision fermentation techniques

Readiness Level – Beyond 5 years

- Health risk prediction, early interventions and targeted treatments
- Population wide health understanding and intervention

Key Sectors

- Healthcare & Medical
- Agriculture
- Environment
- Defence & Defence Industry
- Energy

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security		X	

Australia's place in the world

The United States has the highest research impact for genomics, and has four institutions in the top ten international institutes. China has the second highest, while Australia has the sixth highest research impact, led by the University of Queensland. This is an area that Australia is particularly strong in and is regarded as punching above its weight. The United States has the highest number of genomics patents, followed closely by China, with Australia ranking 13th.

While Australia's venture capital (VC) investment is unranked internationally, high levels of federal and state government investment has resulted in many public/academic-private partnerships. For example, the Illumina-University of Melbourne Genomics Hub, established in December 2020, is leading two flagship genomic innovation projects: development of new genomic-based technologies for simpler and more effective diagnosis of the most challenging-to-treat cancers, and a novel platform to understand the varied types of disease progression of patients with COVID-19, which will help to identify best-suited treatments for individual patients.

In addition to infrastructure investment, the Australian Government has recently established a Medicare-funded genetic testing regime to determine carrier status of genetic conditions such as cystic fibrosis and spinal muscular atrophy, recognising the importance of this technology for people planning pregnancy.

Opportunities and Risks

The Australian Government has recognised the importance of genomics to society's health outcomes and has invested heavily in human genomics research and diagnostic capabilities. Opportunities exist to further connect research institutions, make strategic international partnerships and improve food security in the longer term. Our expertise in genomics has us well positioned to develop new and sophisticated treatments for chronic diseases and cancers, create opportunities to avoid some inherited diseases, and improve our future pandemic preparedness. Research in this area is well coordinated nationally and has strong international partnerships and collaborations, which translates to better healthcare outcomes for Australians from screening to treatment development.

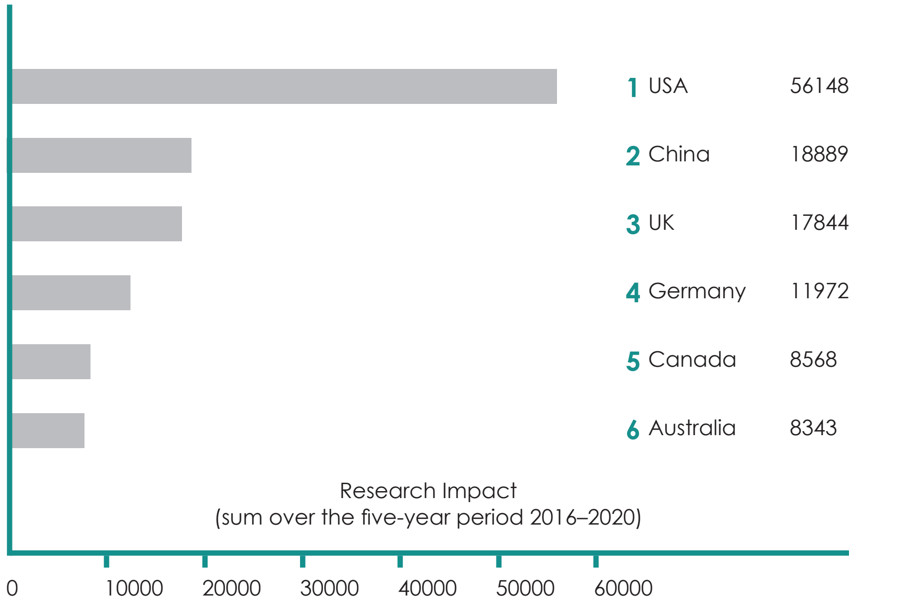
Our strength in genomic research also contributes to our capabilities in downstream applications, such as synthetic biology and other 'omics technologies such as metabolomics and proteomics. However, without appropriate regulation there is a risk of genomic information being used to discriminate against individuals, such as for health insurance, or for broader demographic stigmatisation and marginalisation.

Challenges identified as a barrier to realising the potential of genomics include:

- Lack of social licence and acceptance of gene therapies and genetic modification, resulting in poor uptake and lack of return on research investment.
- Lack of trust, culturally appropriate engagement, governance (including uniform consent and privacy arrangements Australia-wide) and acceptance of data sharing (including for secondary purposes that an individual may not agree with), resulting in lack of utility in genetic and genomic data and adding to the lack of social licence and acceptance of the technologies.
- Insufficient secure and cost-effective data infrastructure to collect, store, manage, access, share and analyse large volumes of data.
- Insufficient engagement with international work, leading to underrepresentation of Australia's diverse population in reference genomes.

Research Impact (RI)

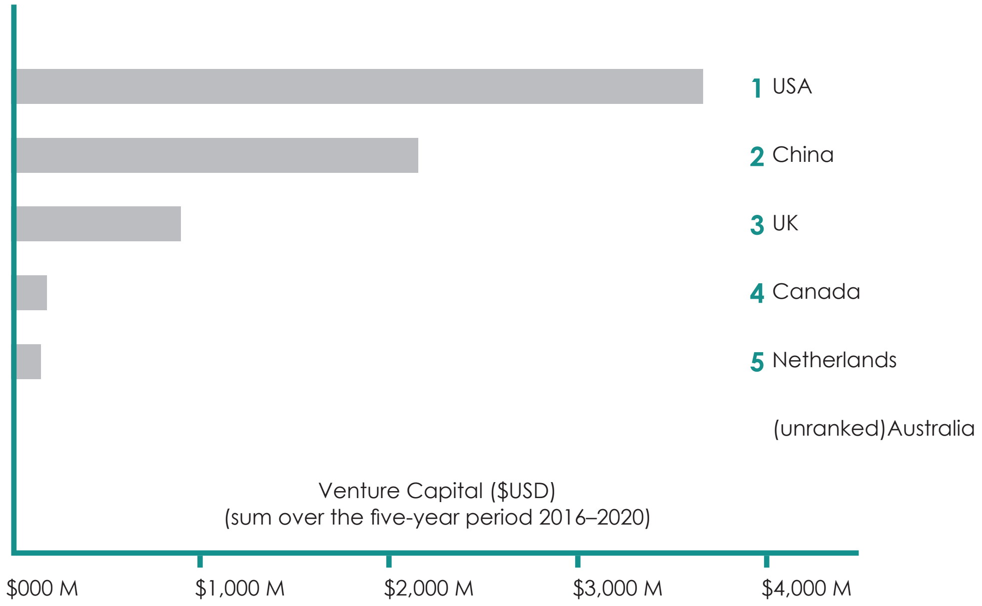
The United States has the highest research impact in this area, with Australia ranked 6th. Total volume of published research has been decreasing at around 3% p.a. over the 5 year period 2016–2020, with 27% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

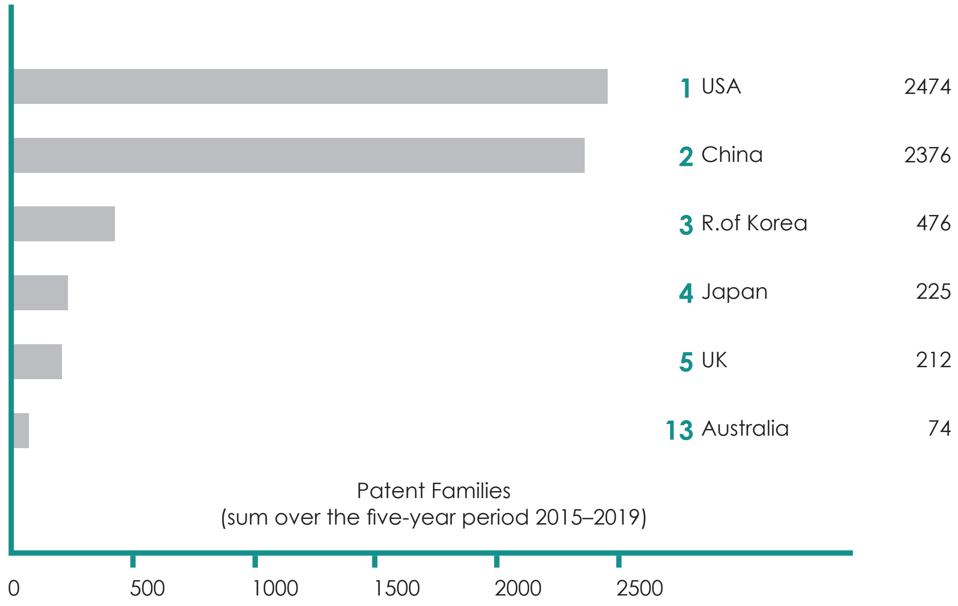
Australia is unranked venture capital (VC) investment for genomics and genetic sequencing. Investment in this area has been growing at 16% p.a. since 2016. The United States has the greatest VC investment in this area, well ahead of China.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

The number of patents filed for this field has increased by 7% annually from 2015 to 2019. Most patents for this technology were filed by applicants or inventors from the United States and China, with Australia ranked 13th.



Research Institutions – International

The United States has 6 institutes in the top 10 international institutions, with Harvard University dominating research impact. The United Kingdom has 2 institutes in the top 10 international institutes.

Rank	Top International Institution	Research Impact
1	Harvard University | United States	6601
2	Massachusetts Institute of Technology | United States	4765
3	University of Cambridge | United Kingdom	4463
4	Seoul National University | South Korea	4338
5	French National Centre for Scientific Research (CNRS) | France	4098
6	Wellcome Sanger Institute | United Kingdom	3946
7	National Institutes of Health | United States	3920
8	Broad Institute | United States	3784
9	Memorial Sloan-Kettering Cancer Center | United States	3713
10	Stanford University | United States	3412

Research Institutions – Australia

Within Australia, the University of Queensland has the highest research impact, and is ranked 29th internationally. Second ranked University of Melbourne is ranked 50th internationally.

Rank	Top Australian Institution	Research Impact
1	University of Queensland	2134
2	University of Melbourne	1343
3	University of Western Australia	951
4	University of Sydney	926
5	University of New South Wales	905
6	Garvan Institute of Medical Research	863
7	University of Adelaide	395
8	Monash University	375
9	CSIRO	342
10	La Trobe University	254

Patents – Australia

Top 5 Australian Patent Applicants	Patent Families
Garvan Institute of Medical Research	7
Monash University	4
University of Melbourne	3
Children's Medical Research Institute	2
SpeeDx	2

Patents filed by Australian businesses, 2015–2019.

Australian Government

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Synthetic Biology

Designing and constructing biological systems and devices that have useful functions not found in nature. Applications for synthetic biology include creating microorganisms that can clean-up environmental pollutants and recycle plastics, manufacturing animal-free meat and dairy products and biological computers.

Key Sectors

- Health
- Agriculture
- Construction
- Manufacturing
- Energy & Environment
- Defence & Defence Industry
- Mining & Resources
- Space
- Transport & Logistics

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security		X	

Key Australian Government Actions

Initiatives

- CSIRO Synthetic Biology Roadmap
- CSIRO Synthetic Biology Future Science Platform
- National Collaborative Research Infrastructure Strategy
- ARC Centre of Excellence in Synthetic Biology
- Modern Manufacturing Strategy
- Low Emissions Technology Statement

Regulations

- Food Standards Australia New Zealand Act 1991
- Gene Technology Act 2000
- Convention on Biological Diversity 1992
- Sanitary and Phytosanitary Agreement 1995
- Cartagena Protocol on Biosafety 2000
- Biological and Toxin Weapons Convention 1975
- Defence and Strategic Goods List 2021

Example Outcomes

- Production of novel biological components and systems with new or optimised functionality, e.g. mRNA vaccines, and nitrogen fixing bacteria
- Improved healthcare outcomes from novel drugs, vaccine development and cell-based therapeutics
- Increased manufacturing of food ingredients and materials, including alternative protein and dairy products
- Reduced carbon emissions through new low emissions production processes
- Improved waste management and natural environment restoration
- Reduced biodiversity loss through the introduction of genetic diversity and genetic improvements to environmental hazards
- Access to growing regional market demand for food products, sustainable textiles, and increased capacity for aid provision
- Improved supply chain resilience to key electronic components, e.g. semiconductors

Opportunities and Risks

Synthetic biology offers a unique opportunity to address many global challenges: meeting the increasing demand for energy and food; mitigating the effects of environmental degradation; and enhancing human and veterinary health and well-being. Synthetic biology could be worth an estimated $700 billion globally by 2040, with the potential for $27 billion annual revenue and 44,000 new jobs for Australia. Increased capability in this area will enable Australia to build new, globally-competitive industries, and enhance existing industries.

As a result of various economic and national security incentives, several major economies are making large investments in synthetic biology capabilities. This includes the United States, the United Kingdom, China, Singapore and South Korea. For example, synthetic biology forms one of 22 strategically important science and technology initiatives in China's 2016 Five-Year Plan. Without focused and coordinated efforts both domestically and internationally, Australia will be unable to leverage its existing research strengths to grow its synthetic biology capabilities. The CSIRO Synthetic Roadmap recognises these opportunities and highlights how we can realise the potential from synthetic biology for Australia.

While synthetic biology will generate economic, social and environmental benefits, it could also be misused – for example, to produce biological weapons, or to alter the germline of animals and humans, or forensic manipulation (criminal perversion). Synthetic biology is reducing the level of technical proficiency required to undertake malevolent acts and is accelerating the emergence of new national security threats, such as biohacking and genetic piracy. Synthetic biology also raises fundamental ethical questions around the relationship between humans and nature, distributive justice, and synthetic biology's benefit or harm to humanity.

Australia is well poised to manage these risks, as its gene technology regulatory system is considered to be among the most effective and progressive in the world. With a proactive approach and a regulatory system that stays up-to-date with new genetic technologies, industry trends and international developments, Australia can have a thriving synthetic biology industry.

Underpinning Science

ANZ Standard Research Classification Category

- Genetics
- Plant biology
- Animal production
- Crop and pasture production
- Fisheries sciences
- Forestry sciences
- Horticultural production
- Agricultural biotechnology
- Environmental biotechnology
- Industrial biotechnology
- Bioinformatics and computational biology
- Medical biotechnology
- Veterinary sciences
- Statistics
- Data management and data science
- Machine learning
- Software engineering
- Applied computing
- Artificial intelligence
- Sociology
- Applied ethics
- Food sciences
- Chemical engineering
- Environmental engineering

Australia's place in the world

The United States has the highest research impact for synthetic biology, and six research institutes in the international top 10. Australia ranks 9th globally for research impact, led by the University of Queensland.

Venture capital (VC) investment globally has been increasing at around 31% p.a. since 2016, with a significant increase in 2020. The United States dominates VC investment, well ahead of the United Kingdom and France. Australia is unranked for VC investment.

While patent activity has been steady since 2016, China and the United States, with similar numbers, have nearly 10 times the number of patents as the remaining top 5 countries (Japan, United Kingdom and Germany). Australia ranks 13th internationally for patent numbers.

The value of synthetic biology to the Australian economy is highlighted in the CSIRO Synthetic Biology Roadmap, with possible synthetic biology-enabled solutions for some of Australia's greatest challenges in the health, biosecurity, environment and agriculture sectors. Return on investment in this area is being realised with numerous spin-out companies producing synthetic dairy products, alternative eggs, and sustainable textiles, as examples.

Example Applications

Readiness Level – Now

- Vaccines, in particular mRNA vaccines
- Biosensor-based diagnostic tools
- Cell-based therapies
- High value food ingredients
- Livestock and aquaculture feed
- Agricultural chemicals
- Biosensors for food safety, quality control and surveillance of conditions or contaminants.
- Waste bioremediation
- Invasive species control
- Engineered cells or enzymes (bio-printing cells, tissue, cartilage)

Readiness Level – 2–5 years

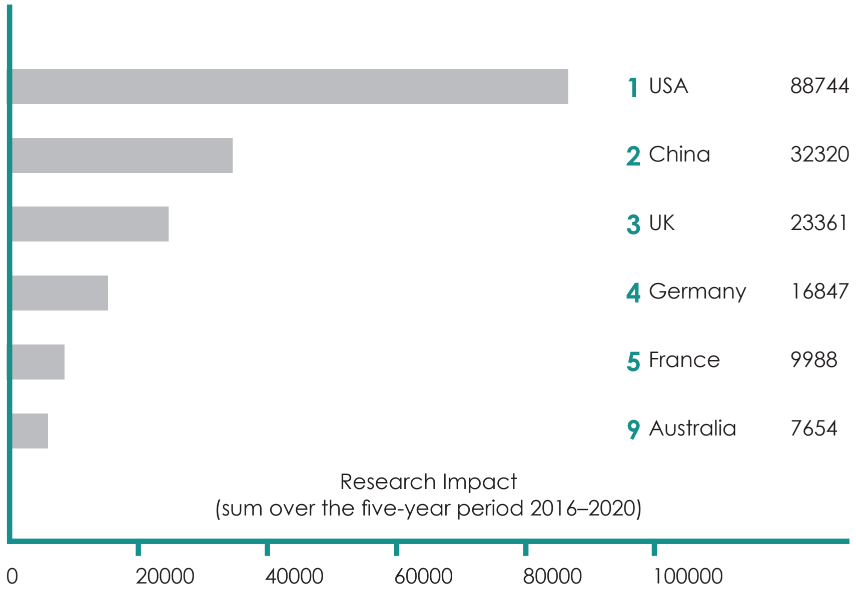
- Repairing of damaged or diseased organs
- Growing new of skin for burn victims
- Improved production methods for foods, animal feed stocks, textile production
- Synthetic probiotics for improved health
- Engineered bio products (coatings, fabrics, materials, sensors)

Readiness Level – Beyond 5 years

- Human augmentation via genetic modifications
- Countermeasures for chemical, biological, radiological and nuclear threats
- Fabrication of entire organs suitable for human transplant such as lung, heart or liver
- Food and medicine production in austere environments (space)
- Theranostic (i.e. combination diagnostic and therapeutic) cell lines for personalised therapies
- Smart materials
- Biological robots
- Longer-lasting and renewable batteries
- Lighter, stronger, tougher materials
- Stronger, more durable adhesives, anti-fouling, anti-corrosion coatings
- Novel dielectric materials for organic energy storage
- Microbial fuel cells for electrical power

Research Impact (RI)

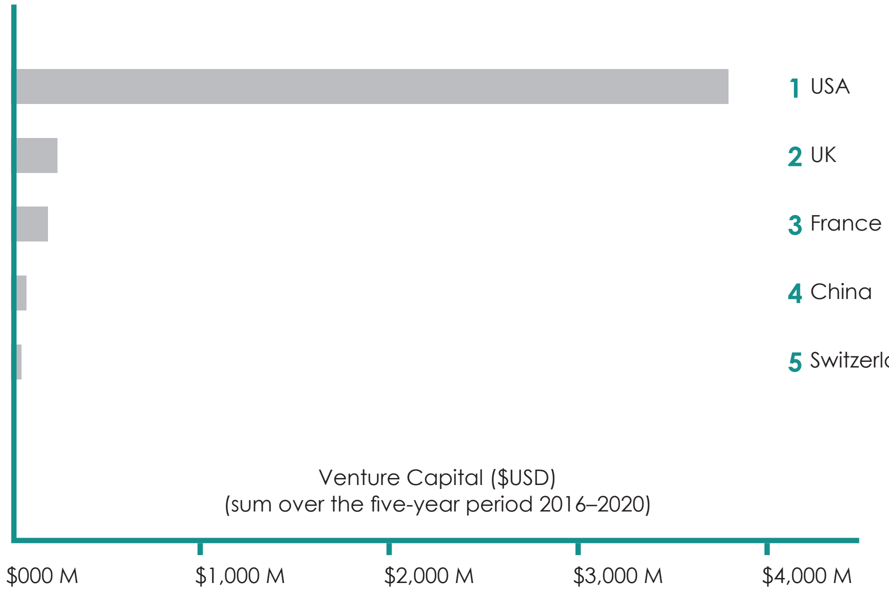
The United States has the highest research impact, with Australia ranked 9th. Total volume of published research has increased at around 3% p.a. over the 5 year period 2016–2020, with 21% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

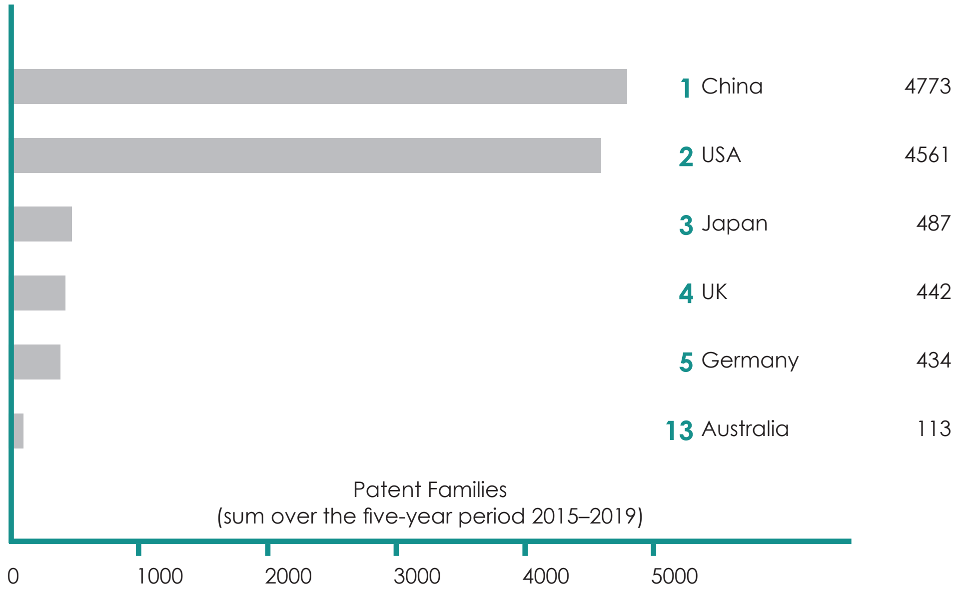
Venture capital (VC) investment is led by the United States, with significantly greater amounts of investment compared to the United Kingdom (2nd) and France (3rd). Australia is unranked for VC investment. Investment in synthetic biology has been growing at 31% p.a. since 2016.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

The number of patents filed annually in this field has remained steady from 2015 to 2019. Most patents in this field were filed by applicants or inventors from China and the United States, with Australia ranked 13th.



Research Institutions – International

Consistent with their overall ranking for research impact, the United States has 6 institutes in the top 10 international institutes. China, France, the United Kingdom and Denmark make up the remaining institutes.

Rank	Top International Institution	Research Impact
1	Harvard University | United States	9363
2	Massachusetts Institute of Technology | United States	8837
3	Chinese Academy of Sciences | China	6132
4	CNRS | France	5645
5	Stanford University | United States	5591
6	United States Department of Energy | United States	4184
7	University of California at Berkeley | United States	3860
8	Howard Hughes Medical Institute | United States	3611
9	Imperial College London | United Kingdom	3480
10	Technical University of Denmark | Denmark	3166

Research Institutions – Australia

Within Australia, the University of Queensland has the highest research impact, followed by the University of Sydney and the University of Melbourne. No Australian university is ranked in the top 50 international institutes.

Rank	Top Australian Institution	Research Impact
1	University of Queensland	1219
2	University of Sydney	1038
3	University of Melbourne	940
4	University of New South Wales	850
5	Monash University	746
6	University of Western Australia	652
7	CSIRO	638
8	Australian National University	618
9	Macquarie University	585
10	University of Adelaide	541

Patents – Australia

Top 5 Australian Patent Applicants	Patent Families
Queensland Institute of Medical Research	7
Benitec Biopharma	5
Calimmune Australia	4
CSIRO	4
CSL Gene Therapy	4

Patents filed by Australian businesses, 2015–2019.

Australian Government

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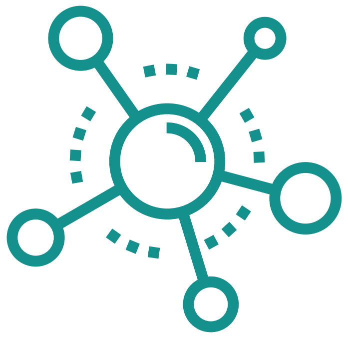
CRITICAL TECHNOLOGIES
POLICY COORDINATION OFFICE

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 become resistant to existing drugs. Examples include drugs to treat Methicillin-resistant Staphylococcus aureus (MRSA) and severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2).

Key Sectors

- Health
- Agriculture
- Education & Research
- Energy & Environment

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security		X	

Key Australian Government Actions

Initiatives

- Resistance joint initiative – Australia's National Antimicrobial Resistance Strategy
- National Microbial Genomics Framework 2019-2022
- Medical Research Future Fund (MRFF) Priority Mission
- National Manufacturing Strategy – Priority area of Medical Products
- National Research Infrastructure (NRI) and 2021 NRI Roadmap
- Agricultural Innovation Policy Statement
- Various Rural RDC priority initiatives

Regulations

- Therapeutic Goods Act 1989
- Therapeutic Goods Regulations 1990
- Defence and Strategic Goods List 2021

Example Outcomes

- Pandemic preparedness and response
- Improved individual health
- Prevention of disease in livestock and companion animals
- Improved public health outcomes
- Reduced mortality and morbidity from infectious and communicable diseases
- Reduce workforce absenteeism due to infectious and communicable diseases

Underpinning Science

ANZ Standard Research Classification Category

- Agricultural biotechnology
- Applied computing
- Applied ethics
- Artificial intelligence
- Biochemistry and cell biology
- Bioinformatics and computational biology
- Clinical sciences
- Data management and data science
- Fisheries sciences
- Genetics
- Immunology
- Industrial biotechnology
- Machine learning
- Medical biotechnology
- Sociology
- Plant biology
- Software engineering
- Statistics
- Veterinary sciences

Example Applications

Readiness Level – Now

- Bacteriophage therapy for bacterial infection
- Antibacterial drugs to deal with new bacterial infections or drug resistant bacteria
- Antiviral drugs to deal with new viruses or drug resistant viruses
- New vaccines against emerging viruses
- Dose regimen optimisation to treat critically ill patients
- Needle-free mechanisms of delivery for vaccines against viral and/or bacterial infections

Readiness Level – 2–5 years

- Improved speed and accuracy for identification and characterisation of bacteria and viruses
- Rapid antibacterial and antiviral drug development in response to new or evolving threats

Readiness Level – Beyond 5 years

- New antibiotics and antivirals that act on different cellular structures, proteins or functions
- Personalised antibacterial and antiviral treatments
- Repurposing of existing pharmaceutical compounds for antimicrobial or antiviral use
- Therapeutic application of naturally occurring compounds for antimicrobial or antiviral use
- Broad-spectrum antibacterial and antiviral drug development to treat novel or unforeseen pathogens

Australia's place in the world

The United States has the highest research impact for novel antibiotics and antivirals, with China second, and Australia 8^{th}. China has the highest number of patents in this area, almost double that of the US, with Australia ranking 15^{th}. Venture capital (VC) investment has been increasing steadily at around 8% p.a. The US has a clear lead in VC investment this area, over China and the United Kingdom. Of note, VC investment in Ireland and Israel ranks 4^{th} and 5^{th} respectively. Australia ranks 10th for VC investment.

The top 10 international institutions comprises a number of different countries, with Harvard University (US) and the Institut national de la santé et de la recherche médicale (France) ranked closely in 1^{st} and 2^{nd}. The University of Melbourne (Australia) is ranked 10^{th}. The diversity of countries represented in the top 10 institutions reflects the global significance of antimicrobial resistance and the urgent need for new antibiotics and antivirals.

Antibiotic and antiviral development is an area where Australia performs strongly in research, with five institutes in the international top 50. This capability is supported by our expertise in genomics and genetic engineering, as well as government commitment to international anti-microbial resistance initiatives.

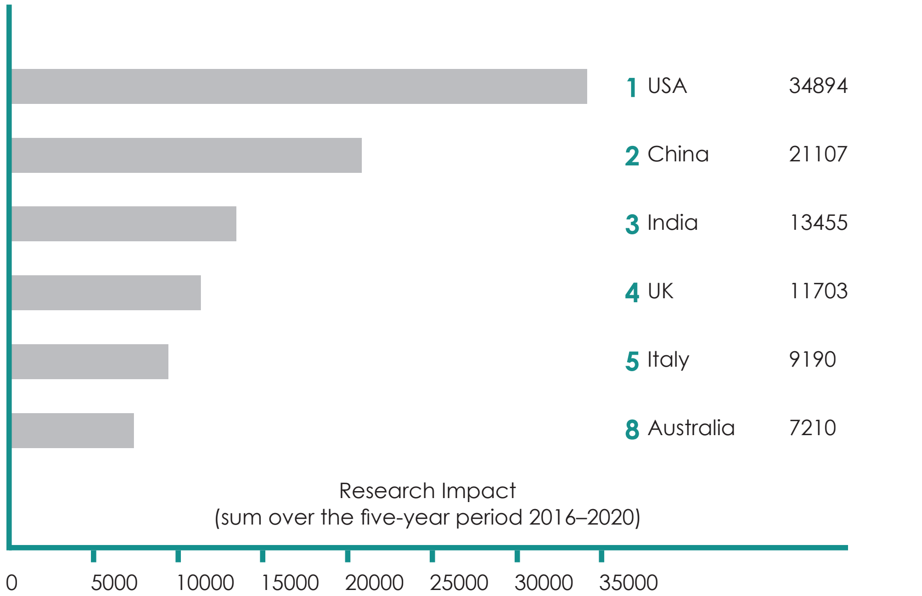
Opportunities and Risks

Maintaining Australia's high standard of living and longevity requires a steady flow of novel antibiotic and antiviral drugs. Every time a person, plant or animal is treated with an antibiotic or antiviral drug there is some risk that the bacteria or virus will develop resistance to that drug. Given enough time the antibiotic and antiviral drugs currently relied on will become less effective or stop working entirely, and infectious diseases that are currently treatable could once again become deadly.As well as protecting Australians from death and disease, novel antibiotics and antivirals have the potential to increase Australia's economic prosperity. Drugs can be exported from Australia or licenced for sale overseas. More effective antibiotics and antivirals can reduce treatment times and shorten or eliminate costly hospital stays. Antibiotics and antivirals with fewer side effects can get people back to work sooner and attract premium pricing in developed economies. Having a 'war chest' of antibiotics and antivirals with different mechanisms of action increases the chances that an effective treatment can be quickly identified and dispensed when a new bacteria or virus emerges to threaten Australian society.

The risks from novel antibiotics and antivirals stem from lacking them when they are needed, and the large amount of time and money that is currently required to discover and develop novel antibiotics and antivirals that are effective and safe to use. Further risks arise from public acceptance. When a safe and effective novel antibiotic or antiviral is approved for use, it likely won't be widely prescribed right away, limiting and delaying the return on investment for developing the drug and also limiting public access. While this may anger investors and potential patients, it limits the opportunities for drug resistance to arise and ensures the drug is available for when it is truly needed.

Research Impact (RI)

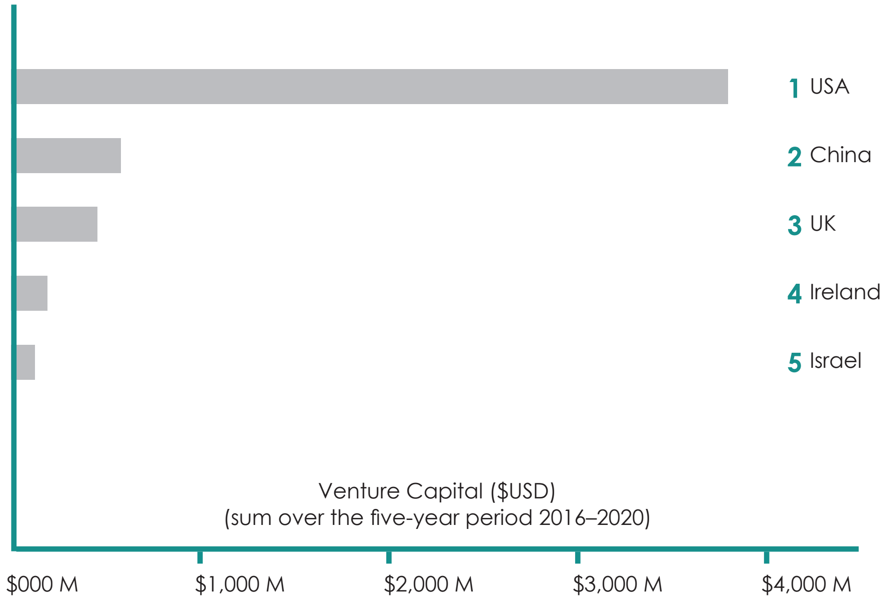
The United States has the highest research impact, with Australia ranked 8th. Total volume of published research has increased at around 8% p.a. over the 5 year period 2016–2020, with 23% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

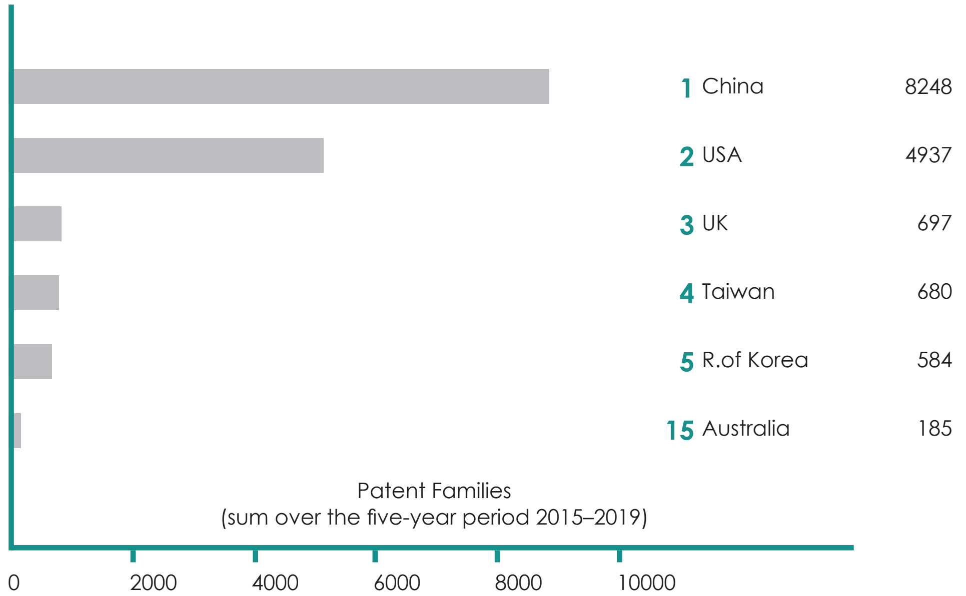
The United States has significantly higher venture capital (VC) investment for novel antibiotics and antivirals, compared to China and the United Kingdom. Australia ranks 10th. Investment in this area has been growing at around 8% p.a. since 2016.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

The number of patents filed for this field has increased by 27% annually from 2015 to 2019. Most patents for this technology were filed by Chinese applicants or inventors ahead of the United States, with Australia ranked 15th.



Research Institutions – International

The top 10 international institutions comprises a number of different countries, with Harvard University (United States) and the Institut national de la santé et de la recherche médicale (France) ranked closely in 1st and 2nd. The University of Melbourne (Australia) is ranked 10th.

Rank	Top International Institution	Research Impact
1	Harvard University | United States	2960
2	Institut national de la santé et de la recherche médicale | France	2958
3	French National Centre for Scientific Research (CNRS) | France	2804
4	Chinese Academy of Sciences | China	2421
5	Imperial College London | United Kingdom	2200
6	University of Oxford | United Kingdom	2071
7	Spanish National Research Council (CSIC) | Spain	1820
8	National University of Singapore | Singapore	1670
9	National Institutes of Health | United States	1650
10	University of Melbourne | Australia	1565

Research Institutions – Australia

Australia has 5 universities in the top 50 international institutions. The University of Melbourne, the highest ranked Australian institute, ranks 10th internationally. The University of Queensland ranks 13th, University of Sydney 25th, University of New South Wales 32nd and Monash University 42nd.

Rank	Top Australian Institution	Research Impact
1	University of Melbourne	1565
2	University of Queensland	1283
3	University of Sydney	1133
4	University of New South Wales	1011
5	Monash University	871
6	Royal Brisbane and Women's Hospital	372
7	University of Adelaide	312
8	Murdoch University	304
9	University of Western Australia	250
10	CSIRO	230

Patents – Australia

Top 5 Australian Patent Applicants	Patent Families
The University of Melbourne	10
Monash University	9
University of Queensland	9
Griffith University	9
University of Sydney	7

Patents filed by Australian businesses, 2015–2019.

Vaccines and medical countermeasures

Tools and techniques to quickly develop and manufacture vaccines, drugs, biologic products and devices used to diagnose and treat emerging infectious diseases and medical conditions caused by exposure to harmful chemical, biological, radiological, or nuclear substances. Applications for vaccines and medical countermeasures include public health emergencies, industrial accidents and defence.

Key Sectors

- Agriculture
- Defence & Defence Industry
- Health

Estimated impact on national interest	Low	Med	High
Economic Prosperity		X	
National Security			X

Key Australian Government Actions

Initiatives

- Antimicrobial Resistance joint initiative – Australia's National Antimicrobial Resistance Strategy
- National Microbial Genomics Framework 2019–2022
- Medical Research Future Fund (MRFF) Priority Mission
- National Manufacturing Strategy – Priority area of Medical Products
- National Collaborative Research Infrastructure Strategy
- Agricultural Innovation Policy Statement
- Various Rural RDC priority initiatives

Regulations

- Therapeutic Goods Act 1989
- Therapeutic Goods Regulations 1990
- Gene Technology Act 2000
- Gene Technology Regulations 2001
- Defence and Strategic Goods List 2021

Example Outcomes

- Pandemic preparedness and response
- Improved health outcomes in emergency settings and industrial accidents
- Improved individual health
- Improved animal health and welfare outcomes
- Reduced mortality and morbidity from infectious and communicable diseases

Underpinning Science

ANZ Standard Research Classification Category

- Agricultural biotechnology
- Applied computing
- Applied ethics
- Artificial intelligence
- Biochemistry and cell biology
- Bioinformatics and computational biology
- Clinical sciences
- Data management and data science
- Fisheries sciences
- Genetics
- Immunology
- Industrial biotechnology
- Machine learning
- Medical biotechnology
- Sociology
- Plant biology
- Software engineering
- Statistics
- Veterinary sciences

Example Applications

Readiness Level – Now

- mRNA vaccine for COVID-19
- Human protection suits
- Vaccines, medicines and therapies
- Diagnostic systems
- Telemedicine and remote diagnostics
- Physiological sensors (smart watches, fitness trackers, telemetric pills)

Readiness Level – 2–5 years

- mRNA vaccines for emerging communicable diseases and cancer causing viruses
- Needle-free mechanisms for vaccine delivery
- Wearables for diagnostic and countermeasure response alerts
- Personalised medicines and therapies
- Hyperspectral snapshot imaging to map chemicals in the landscape
- Next-generation respirators and air purifiers

Readiness Level – Beyond 5 years

- Organ-on-a-chip sensors to detect pathogens and chemicals
- Rapid diagnostics and therapies (convergence biomarkers, genetic therapies and smart materials)
- Personalised medical diagnosis and treatment (enabled through genome sequencing, genetic engineering and synthetic biology)
- Auto-detect, diagnose and response systems (countermeasures without human intervention)
- Tissue barriers (topical skins, mucosal surfaces)
- Quantum spectroscopy to detect small concentrations of chemicals and biologicals
- Quantum gravity sensors to detect shielded nuclear materials

Opportunities and Risks

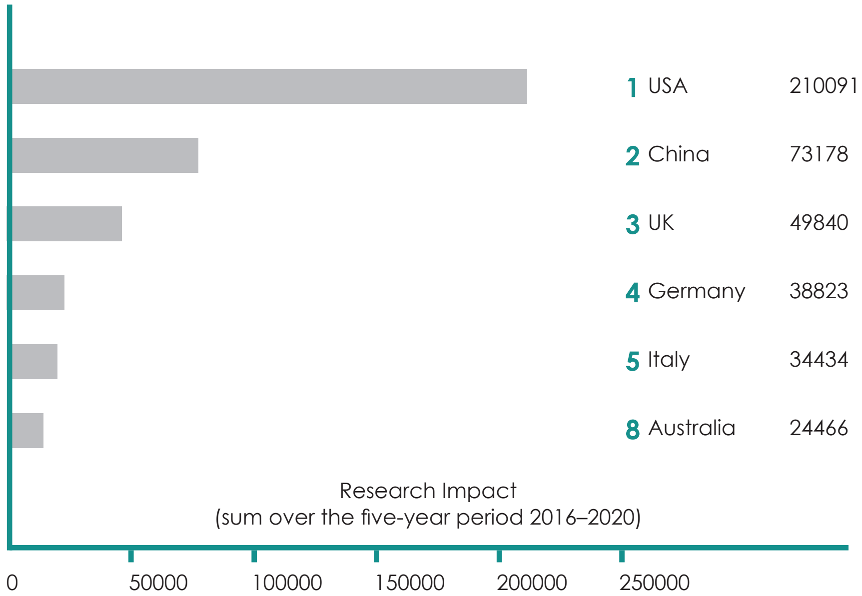
Advancements in vaccine and medical countermeasure technologies will lead to better health outcomes and reduced stress on paramedic and hospital systems. Vaccines are an essential preventative public health measure to protect populations from communicable diseases. With Australia's strengths in the genomics and genetic engineering, as well as strong international collaborations in these areas, Australia is well positioned to continue contributing to these outcomes.
Australia's pivot to sovereign vaccine manufacturing during COVID-19 pandemic also demonstrated the great potential that exists in vaccine R&D. Throughout the period, several domestic universities developed novel vaccine candidates for the COVID-19. Moreover, some businesses adapted to then manufacture the candidates. With continued funding and research, vaccine development such as this may help Australia obtain vaccine security as well as export opportunities.
Medical countermeasures promise the development of better sensors (persistent, sensitive, rapid and remote) which can be combined with enhanced diagnostics to enable time-compliant detection and intervention of threats – and thereby reduce their exposure to populations. The improved efficacy of countermeasures to chemical, biological, radiological and nuclear (CBRN) threats and epidemics will also be realised through enhanced preparedness, rapid and more accurate diagnostics, and personalised therapies.
CBRN threats are expected to increase, as vaccine and medical countermeasure technologies may be misused by malevolent actors to create chemical or biological warfare agents. Being aware of this risk and developing means to protect our assets will be essential. Additionally, through the democratisation and accessibility of technologies, the intellectual property of technology may be compromised.
From a societal perspective, there may also be ethical and religious reluctance to the acceptance of new sensors, monitoring systems, drugs and treatments. A lack of acceptance may limit uptake and impede the development of population-wide protection. There may also be concerns associated with data privacy from the collection and storage of medical histories (e.g. biomarkers and therapeutic reaction data).

Australia's place in the world

The United States has the highest research impact for vaccines and medical countermeasures, with nearly three times that of second-ranked China and more than eight times Australia. However, China has the highest number of patents – over double that of the United States – while Australia ranks 13th. Venture capital (VC) investment in this field has been increasing at around 34% p.a. The United States has a significant lead in venture capital investment over China and Germany (ranked 2nd and 3rd respectively). Australia ranks 19th for VC investment in this area.
8 of the top 10 international institutions are from the United States, which is consistent with the overall research impact of the United States. Australia has 3 institutes in the top 50 – the University of Melbourne (29th), the University of Sydney (30th) and Monash University (40th). The latter, Monash University, developed a vaccine candidate during the COVID-19 pandemic while the former two have been allocated funding for vaccine research.
A significant increase in VC investment occurred between 2019 and 2020, consistent with increased activity in vaccine and countermeasure research in response to the global COVID-19 pandemic. Traditionally, medical countermeasures have been linked with defence priorities; however, COVID-19 and other disease outbreaks have highlighted the broader necessity of vaccine and medical countermeasure development.

Research Impact (RI)

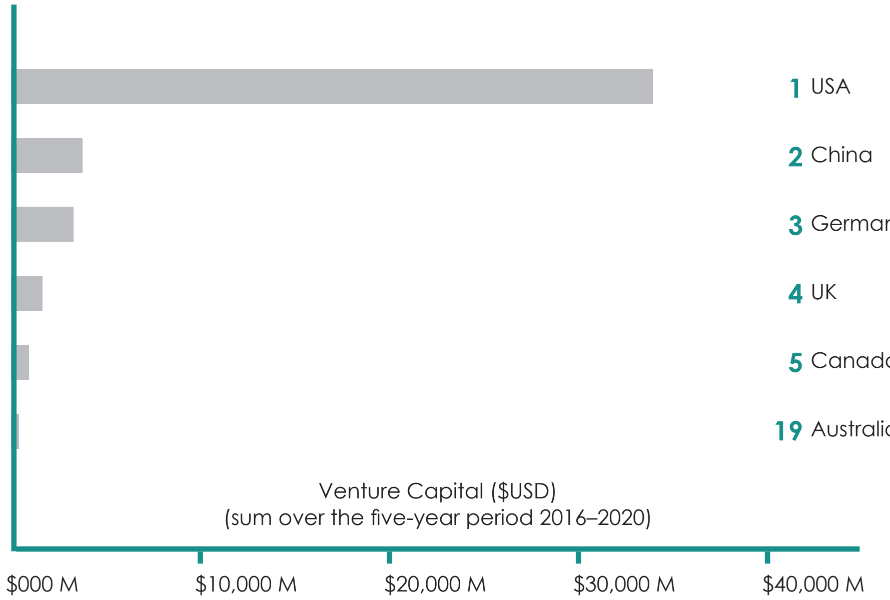
The United States has the highest research impact, with Australia ranked 8th. Total volume of published research has increased at around 35% p.a. over the five-year period 2016–2020, with 24% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality

VC Investment

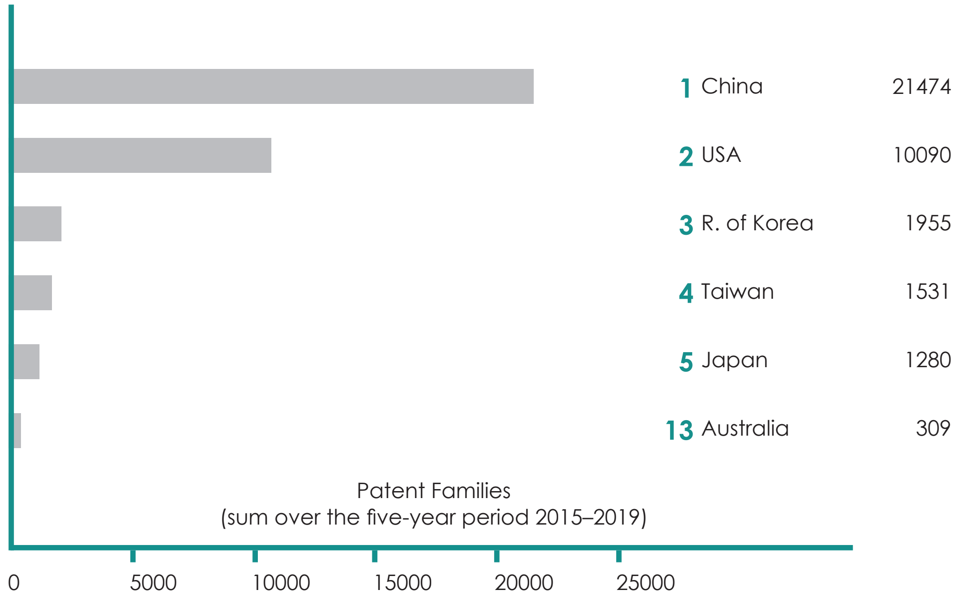
The United States has significantly higher amounts of venture capital (VC) investment, well ahead of China (2nd), and Australia 19th. Investment in this area has been growing at around 34% p.a. since 2016.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

Most patents for this technology were filed by Chinese applicants or inventors, almost double the number of the United States. Australia is ranked 13th with 309 patents first filed here. The number of global patent filings in this field has remained steady from 2015 to 2019.



Research Institutions – International

The United States has 8 institutes in the top 10 international institutions, with 4 institutes in the top 5. France and the United Kingdom make up the top 10 international institutes.

Rank	Top International Institution	Research Impact
1	Harvard University | United States	27849
2	National Institutes of Health | United States	17913
3	University of Pennsylvania | United States	17467
4	Johns Hopkins University | United States	15901
5	Institut national de la santé et de la recherche médicale | France	14148
6	Stanford University | United States	12919
7	University of Washington | United States	9873
8	University of Texas MD Anderson Cancer Center | United States	9598
9	University College London | United Kingdom	9435
10	Duke University | United States	9136

Research Institutions – Australia

Australia has 3 institutions in the top 50 international institutions. The University of Melbourne, which has the highest research impact in Australia, is ranked 29th globally. The University of Sydney is ranked 30th, and Monash University is ranked 40th.

Rank	Top Australian Institution	Research Impact
1	University of Melbourne	6351
2	University of Sydney	6348
3	Monash University	5381
4	University of Queensland	3373
5	University of New South Wales	2017
6	University of Western Australia	1414
7	Peter Maccallum Cancer Centre	1018
8	University of Adelaide	897
9	Griffith University Queensland	523
10	Hudson Institute of Medical Research	513

Patents – Australia

Top 5 Australian Patent Applicants	Patent Families
Queensland Institute of Medical Research	20
University of Sydney	10
Monash University	9
Griffith University	7
Cynata Therapeutics	5

Patents filed by Australian businesses, 2015-2019.

Biofuels

Solid, liquid or gas fuels produced from biological or organic sources. Examples include biogas and biodiesel derived from plant biomass, and bioethanol from crops such as corn and sugar cane.

Key Sectors

- Agriculture
- Transport & Logistics
- Defence & Defence Industry

Estimated impact on national interest	Low	Med	High
Economic Prosperity		X	
National Security		X	

Key Australian Government Actions

Initiatives

- Clean Energy Finance Corporation
- Australian Renewable Energy Agency (ARENA) – projects
- Modern Manufacturing Strategy – clean energy priority
- Low emissions partnerships with Germany, Singapore, Japan and the United Kingdom
- Quad clean energy partnership

Regulations

- Fuel Quality Standards Act 2000
- Renewable Energy (Electricity) Act 2000

Example Outcomes

- Reduced emissions from increased utilisation of alternative fuels
- Improved supply chain resilience through increased local production of alternative liquid fuels
- Reduced dependence on external strategic resources/materials and external supply chains
- Diversified energy supply
- Biomass waste generated from creation of biofuels is recycled and used in other industries (e.g., biodiesel residues used in compost or for animal feeding)
- Vertical farming biomass as a way to convert electrical energy into liquid or gas biofuels for transportation
- Increased agricultural productivity from higher value products particularly from declining-value products such as sugar

Underpinning Science

ANZ Standard Research Classification Category

- Agricultural biotechnology
- Automotive engineering
- Chemical engineering
- Electrical engineering
- Fluid mechanics and thermal engineering
- Mechanical engineering
- Physical chemistry
- Electronics, sensors and digital hardware
- Resources engineering and extractive metallurgy
- Plant biology
- Crop and pasture production
- Food sciences
- Environmental engineering
- Environmental biotechnology

Example Applications

Readiness Level – Now

- Supplement/alternative to petrol and diesel fuels for transport
- Power generation, including land-fill gas power plants
- Heating for homes and businesses
- Cleaning agent for oil spills and grease
- Solvent for paint and adhesive removal
- Engine lubricants

Readiness Level – 2–5 years

- Expanded trials in the aviation industry
- Biofuel cells for powering consumer electronics

Readiness Level – Beyond 5 years

- Proliferation and significant use of biofuel in the aviation industry
- Trials for maritime transportation, including biofuel-powered warships
- High quality (group III) engine oils
- Combined photoelectric and microbial fuel cells for increased power production
- Sweat-powered wearables

Australia's place in the world

India has the highest research impact for biofuels and, along with Malaysia, has 3 institutes in the top 10 international institutions. Australia is ranked 10th, with 3 institutes in the top 50 international institutions. The United States has the highest amount of venture capital (VC) investment, well ahead of India (2nd) and Finland (3rd), with Australia unranked. China has the greatest number of patents for biofuels, with around 5 times the amount of the United States, which is ranked 2nd. Australia is ranked 23rd for patents internationally.

Currently, Australia has limited industrial production capability for biofuels, contributing to an insignificant portion of the market share. For example, domestic production of biodiesel is appropriately 1% of total domestic diesel consumption. Bioenergy (including biofuels) constituted 5% of total clean energy generated in Australia in 2020, equating to 1.4% of total energy generated in Australia. While Australia does not currently have domestic capability to produce aviation biofuel, Australian airlines have committed to increasing their use of biofuels on flights from 2020 onwards.

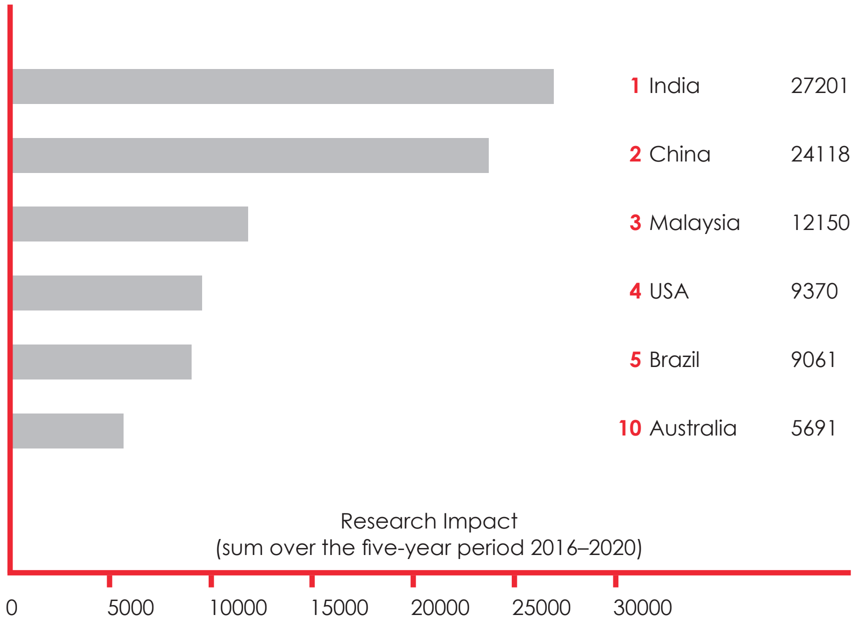
Opportunities and Risks

Biofuels are a potential source of renewable energy. Although Australia's biofuel industry is small, there are opportunities to leverage Australia's existing capabilities in this industry, along with our expertise in agriculture, forestry and engineering to expand the domestic biofuel industry. Building capability and leveraging our existing expertise in agricultural production and arable land could increase Australia's production of biofuels, in turn creating economic opportunities and employment for regional and rural areas, and expanding export opportunities. There is also significant potential to use less productive land to grow hardier or slower-growing biomass sources. Investment and proliferation of biofuel and bioenergy technologies and the growth of the industry may also achieve substantial socioeconomic and geopolitical benefits by lessening dependence on imported oil, gas and other strategic resources. Ample local supplies of alternative fuels such as biofuels will reduce the impact of international resource price fluctuations.

There is a risk that increased demand for biofuels may displace food production, particularly as several biofuel feedstock crops are also foodstuffs for humans and animals. Changing land use to grow biofuel feedstock, and biofuel processing practices, may each increase greenhouse emissions.
As biofuel demand increases, nations may use production capabilities as a geostrategic asset. Attempts to undermine biofuel use or exports may create economic and strategic risks for Australia, particularly if Australia seeks to position itself as a key regional supplier.

Research Impact (RI)

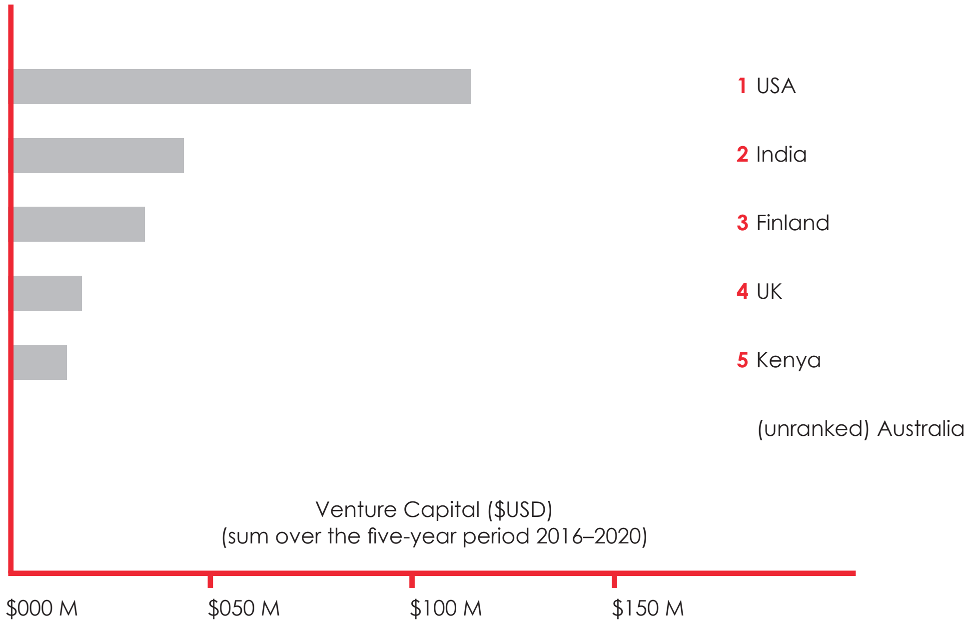
India has the highest research impact ahead of China and Malaysia, with Australia ranked 10th. Total volume of published research has increased at around 7% p.a. over the 5 year period 2016–2020, with 7% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

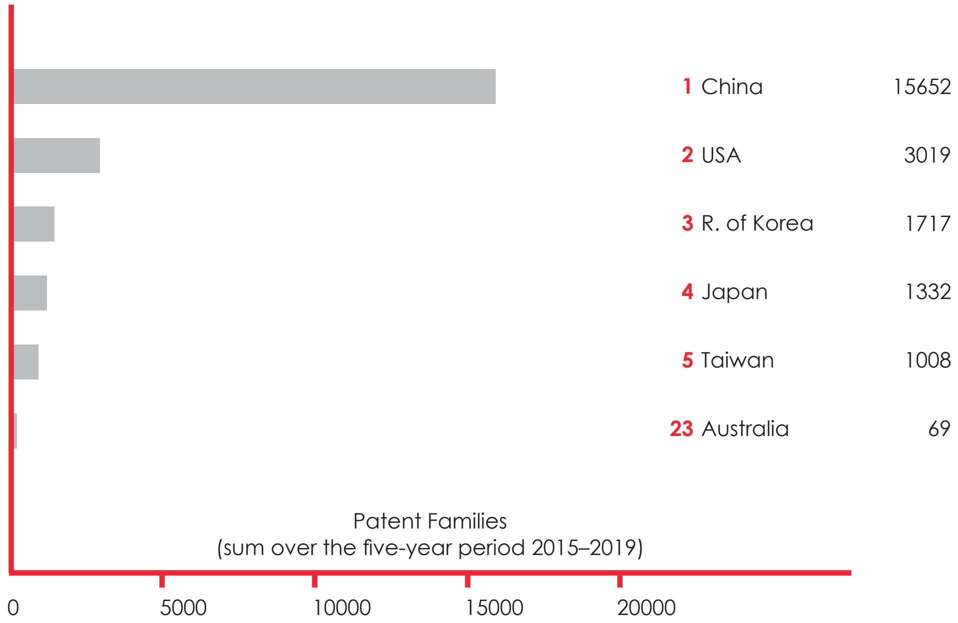
Australia is unranked for venture capital (VC) investment in biofuels, and the United States has significantly greater investment than India and Finland. Globally VC investment into biofuels has increased by around 1% p.a. over the past 5 years.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

The highest number of patents in this technology were filed by applicants or inventors in China, with around 5 times the number of the 2nd ranked United States. Australia ranks 23rd. Overall patent applications have been decreasing at around 13% p.a. since 2015.



Research Institutions – International

India and Malaysia each have 3 institutes in the top 10 international institutions for research impact. China, Iran and Denmark make up the remainder of the top 10 international institutions.

Rank	Top International Institution	Research Impact
1	Anna University | India	5428
2	University of Malaya | Malaysia	3437
3	Chinese Academy of Sciences | China	2539
4	University of Tehran | Iran	2289
5	Technical University of Denmark | Denmark	1898
6	Sathyabama University | India	1837
7	Vel Tech University | India	1612
8	Tsinghua University | China	1602
9	University Malaysia Pahang | Malaysia	1563
10	Universiti Teknologi Malaysia | Malaysia	1511

Research Institutions – Australia

Within Australia, the University of Technology Sydney has the highest research impact and is ranked 30th internationally. Internationally, Central Queensland University and the University of Queensland are ranked 33rd and 45th respectively.

Rank	Top Australian Institution	Research Impact
1	University of Technology Sydney	965
2	Central Queensland University	930
3	University of Queensland	764
4	Queensland University of Technology	560
5	University of New South Wales	525
6	University of Wollongong	425
7	Curtin University	419
8	Royal Melbourne Institute of Technology University	397
9	University of Southern Queensland	343
10	Deakin University	222

Patents – Australia

Top 5 Australian Patent Applicants	Patent Families
CSIRO	6
Microbiogen	5
Crucible Group	2
Environmental Engineers International	2
Herman Bio Energy International	2

Patents filed by Australian businesses, 2015–2019.

Australian Government

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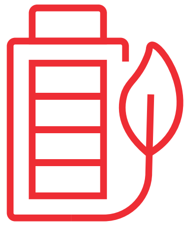
Electric batteries



Devices that produce electricity from stored electrochemical energy and tolerate multiple charge and discharge cycles. Electric batteries utilise various materials and chemistries (e.g. lithium-ion (Li-ion), nickel metal hydride (Ni-MH)) battery and form factors (e.g. flow batteries for stationary grid storage, polymer electrolytes for vehicles and personal devices).

Key Sectors

Influences all sectors of the economy, including:

- Agriculture
- Defence and Defence Industry
- Energy and environment
- Health
- Manufacturing
- Mining and resources
- Space
- Transport and logistics

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security		X	

Key Australian Government Actions

Initiatives

- Future Fuels Strategy
- Australian Research Council Training Centre for Future Energy Storage Technologies
- CSIRO Centre for Hybrid Energy Systems
- CSIRO Stored Energy Integration Facility
- Relectrify Second-Life Battery Trial
- Grid Reliability Fund
- Next Generation Electric Bus Depot
- United Energy Low Voltage Battery Trial
- Low-Voltage (LV) Grid Battery Energy Storage Systems Trial

Regulations

- Defence and Strategic Goods List 2021

Example Outcomes

- Improved reliability and usefulness of many consumer products including smart-phones, smart-watches, and laptops
- Greater capacity for renewable energy to replace traditional forms of power production, irrespective of weather or time-of-day
- Increased capability and proliferation of robotic devices
- Increased versatility of location and independence of digital systems
- Increased range and faster charging of electric vehicles
- Increased resilience of the electricity grid

Underpinning Science

ANZ Standard Research Classification Chemistry

- Electronics, sensors and digital hardware
- Electrical engineering
- Geology
- Materials engineering
- Mining engineering
- Analytical chemistry
- Chemical engineering
- Physical chemistry

Example Applications

Readiness Level – Now

- Portable electronic devices, e.g. wearable devices, mobile phones, remote sensors, laptop computers, emergency beacons
- Electric and hybrid vehicles for logistics and transportation
- Temporary storage of excess energy supply (e.g. wind, solar)
- Electric helicopters with an 80km range and a speed of up to 120km/h (e.g. the CityAirbus NexGen)
- Grid scale batteries at scales of around 200MW

Readiness Level – 2–5 years

- Cheaper, safer batteries with moderate power improvements
- More resilient power supplies for communication, computing and sensor devices in adverse environments
- Distributed batteries through the electricity grid coordinated to improve network utilisation and enable increased electrification (e.g. electric vehicle charging)

Readiness Level – Beyond 5 years

- Electric airplanes capable of transporting over 150 passengers
- Large (GW) scale grid batteries removing the need for instantaneous generation/consumption balance and significantly improving grid resilience
- Lighter, safer and more powerful batteries, primarily driven by demand for longer-range electric vehicles
- Flexible micro batteries for bio-sensors, wearable electronics and smart contact lenses
- Cheap liquid and/or metal-air battery designs for large-scale energy storage where weight and power flexibility are less important
- New battery designs to enable devices to operate at low temperatures; i.e. subsea (-40°C), high-altitude aircraft (-50°C), polar sites (-80°C), space satellites (-160°C)
- New battery designs with low reliance on critical minerals and rare earths

Australia's place in the world

China dominates across research impact, venture capital and patents in electric batteries. China has the highest research impact, significantly higher than the rest of the world, including the United States. Chinese research institutions also occupy 4 of the 5 top ranking positions, with the US Department of Energy ranking 3rd. Australia is ranked 5th in the world, with the University of Wollongong our highest ranked institution at 23rd.

Australia is ranked 4th for venture capital (VC) investment globally, behind China, the United States and Japan. Globally, VC investment has been increasing at 34% annually since 2016. Considerably more patents have been lodged by applicants or inventors from China, with almost 4 times as many patents compared to Japan or the United States. Australia ranks 17th.

Australia is a significant producer of important inputs to batteries, including many critical minerals and renewable energy, and has world-class skills and research capability to design and develop battery technology. This situates Australia competitively to service much of worldwide demand for these high-tech goods. As Australia transitions towards renewable energy, we have the opportunity to become a major exporter of renewable energy into our region.

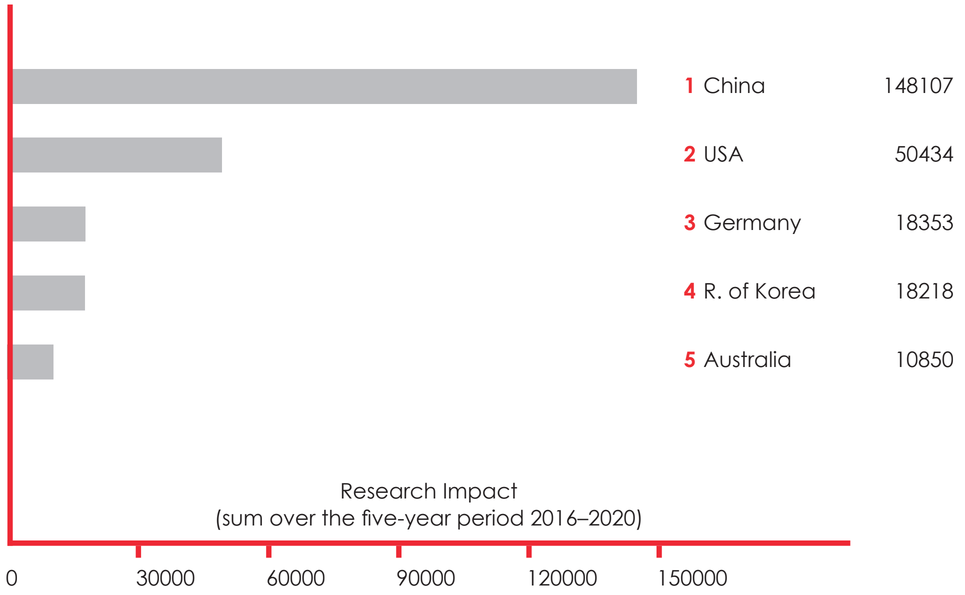
Opportunities and Risks

Electric batteries will be crucial in the transition to a renewable energy future. Electric batteries will be essential to power consumer electronics, households, support manufacturing energy needs and enable sustainable transportation. Improved storage capacity, decreased size, extended life and expected reductions in cost will also see an increase in the value of batteries for electricity supply. Australia is well placed to take advantage of the growing demand for electric batteries within our region and globally. Our role in the transition to renewables internationally will be underpinned by our world-class research (including technologies for battery integration and managing battery use to extend operational life), our natural resources and our expanding domestic industry—all of which are required for battery production. The global supply chain for batteries is currently hourglass shaped with central fragility, due to the concentration of processing technologies with a single supplier. Australia is ideally placed to play a key role in addressing this by building alternative supply chains.

Australia must carefully consider and mitigate the end-of-life risks associated with electric batteries, and improve recovery and recycling efforts for components. Whilst greater battery utilisation is a desirable outcome, we must also be aware of potential pressures on our emerging renewable grid and the possibility that battery affordability may be impacted. As batteries become more prevalent, particularly for domestic use, the public must have access to reliable information about best practices around battery use and preservation.

Research Impact (RI)

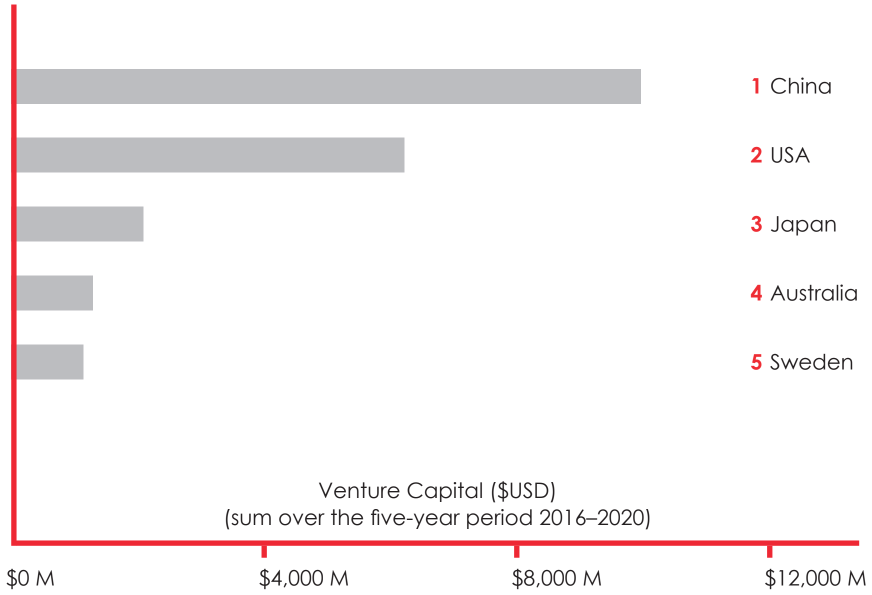
China has the highest research impact in this area, ahead of the United States. Australia is ranked 5th. Total volume of published research has been increasing at 8% p.a. over the 5 year period 2016–2020, with 20% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

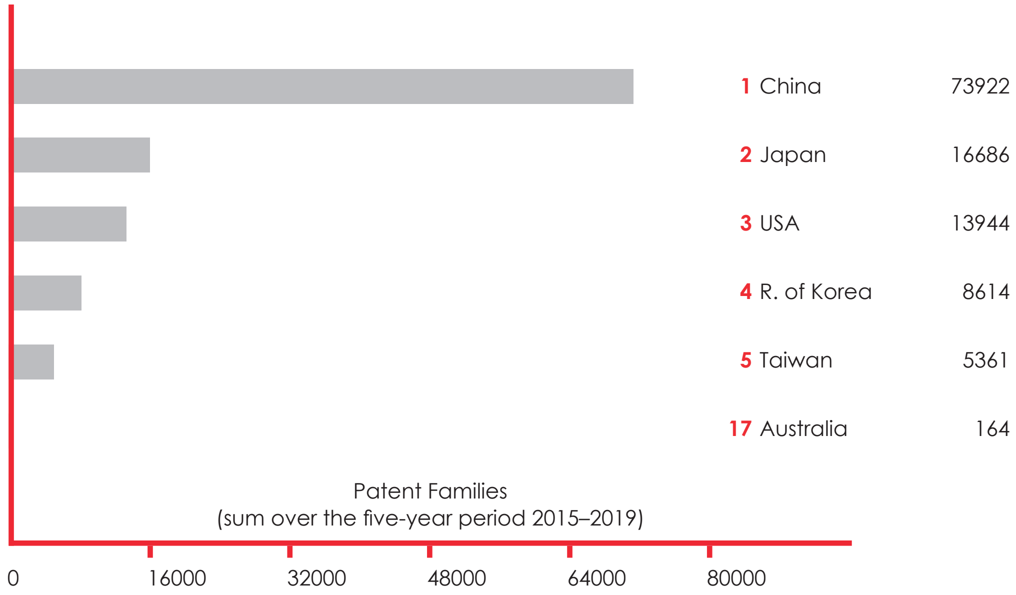
China has the highest amount of VC investment for electric batteries, ahead of the United States, and Australia is ranked 4th. Investment in this area has been growing at 34% p.a. since 2016.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents - International

The number of patents being lodged annually in this field has been increasing by 34% since 2015. Most patents in this field were filed by applicants or inventors from China. Australia is ranked 17th.



Research Institutions - International

China has 7 institutions in the top 10 international institutions. Institutions from the United States and Singapore make up the remaining top 10.

Rank	Top International Institution	Research Impact
1	Chinese Academy of Sciences | China	20753
2	Tsinghua University | China	9875
3	United States Department of Energy | United States	8999
4	Beijing Institute of Technology | China	8070
5	University of Chinese Academy of Sciences | China	7135
6	University of Science and Technology of China | China	6766
7	Central South University | China	6679
8	Argonne National Laboratory | United States	6293
9	Nanyang Technological University | Singapore	5549
10	Zhejiang University | China	5341

Research Institutions - Australia

Within Australia, the University of Wollongong has the highest research impact, and is ranked 23rd internationally. No other Australian institute is ranked in the top 50.

Rank	Top Australian Institution	Research Impact
1	University of Wollongong	3122
2	University of New South Wales	1259
3	University of Queensland	1071
4	Griffith University	1063
5	University of Technology Sydney	948
6	Swinburne University of Technology	939
7	Queensland University of Technology	808
8	Deakin University	768
9	Curtin University	488
10	Royal Melbourne Institute of Technology University	437

Patents - Australia

Top Australian Patent Applicants	Patent Families
University of Wollongong	5
Deakin University	4
Monash University	4
Newsouth Innovations	4
Gelion Technologies	3

Patents filed by Australian businesses, 2015–2019.

Data current as at 16 March 2022.

Hydrogen and ammonia for power

Sustainable production, storage, distribution and use of hydrogen (H_2) and ammonia (NH_3) for heat and electricity generation. Hydrogen and ammonia are potential low or zero emission, zero-carbon alternatives to fossil fuels and electric batteries. Applications for hydrogen and ammonia as a fuel source include aviation and marine transport, long distance road transport and heating.

Key Sectors

- Agriculture
- Energy & Environment
- Construction
- Defence & Defence Industry
- Manufacturing
- Mining & Resources
- Transport & Logistics

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security			X

Key Australian Government Actions

Initiatives

- National Hydrogen Strategy
- National Hydrogen Roadmap
- Australian Renewable Energy Agency (ARENA) – projects
- Modern Manufacturing Strategy – clean energy priority
- Clean Hydrogen Industrial Hubs Program
- Clean Energy Finance Corporation (CEFC)
- Low emissions partnerships with Germany, Singapore, Japan and the United Kingdom
- Quad clean energy partnership

Regulations

- Australian Energy Market Act 2004 (Cth)
- Renewable Energy (Electricity) Act 2000 (Cth)
- Road Vehicle Standards Act 2018 (Cth)
- Australian Energy Market Agreement

Example Outcomes

- Reduced carbon and methane emissions from increased utilisation of alternative fuels
- Improved stability of the electricity grid
- Diversified and stabilised energy supply
- Improved supply chain resilience of fuel supply from increased local production of alternative fuels
- Reduced transportation and logistics costs from locally produced fuels
- Diversified export resources

Underpinning Science

ANZ Standard Research Classification Category

- Analytical chemistry
- Inorganic chemistry
- Macromolecular and materials chemistry
- Physical chemistry
- Automotive engineering
- Chemical engineering
- Electrical engineering
- Electronics, sensors and digital hardware
- Fluid mechanics and thermal engineering
- Materials engineering
- Mechanical engineering
- Resources engineering and extractive metallurgy
- Atomic, molecular and optical physics
- Classical physics
- Condensed matter physics

Example Applications

Readiness Level – Now

- Some electric vehicles, including cars, buses, fork lifts, construction vehicles, through the use of hydrogen fuel cells
- Dual-powered (hydrogen/diesel) farming equipment
- Diesel-electric submarines, such as the German Type 212
- Industrial chemical feedstock
- Hydrogen-fuelled gas turbines for power production
- Hydrogen rocket fuel for space travel

Readiness Level – 2–5 years

- Blending hydrogen in the gas network
- Hydrogen internal combustion engines
- Ammonia as a carrier for hydrogen
- Ammonia-fuel blends for combustion engines
- Large-scale hydrogen fuel cells for factories
- Green ammonia production

Readiness Level – Beyond 5 years

- Conversion of the gas network to using hydrogen
- Fuel for mining vehicles, long distance trucks, trains
- Fuel for cargo and container ship
- Ammonia internal combustion engines
- All-ammonia fuel cells

Australia's place in the world

China has the highest research impact in this field, significantly ahead of the second-ranked United States. Australia ranks 9th for research impact, led by the University of New South Wales and Curtin University which both feature in the top 50 international institutes.

Venture capital (VC) investment has increased at around 28% p.a. from 2016–2020, with the United States having the highest amounts of VC investment. Canada, the United Kingdom, Israel and the Russian Federation make up the top 5 countries for VC investment. Australia has the 10th highest amount of VC investment globally.

Patents in this area have been increasing by around 3% p.a. since 2015. China dominates the number of patents in this area, with almost 3 times the amount of the second-placed United States. Australia ranks 19th.

As articulated in the 2019 National Hydrogen Strategy, the Australian Government recognises the importance of hydrogen in the country's energy mix as an emerging power source. Australia has the opportunity to be world leading in its use of hydrogen and ammonia for power, both in terms of its research and potential export to overseas markets. Continual research and investment to more effectively extract and store hydrogen, as well as its safe export, could place Australia as a key export partner for countries with energy needs.

Opportunities and Risks

The growth of technologies to extract hydrogen and ammonia as power sources presents not only opportunities for exports to existing and emerging markets, but for promoting Australia as a reliable source of hydrogen. Hydrogen is increasingly being considered in other countries' energy mixes as a clean source of energy that can contribute to green energy targets. For example, Japan has set an ambitious target of 800,000 hydrogen fuel cell vehicles by 2030, with South Korea committing to 630,000 hydrogen fuel cell vehicles by 2030. Australia currently has 16 hydrogen projects underway, with a further 10 projects at an advanced stage of development planning. These investments could generate more than 8000 jobs, many in regional Australia, and contribute $11 billion to GDP by 2050.

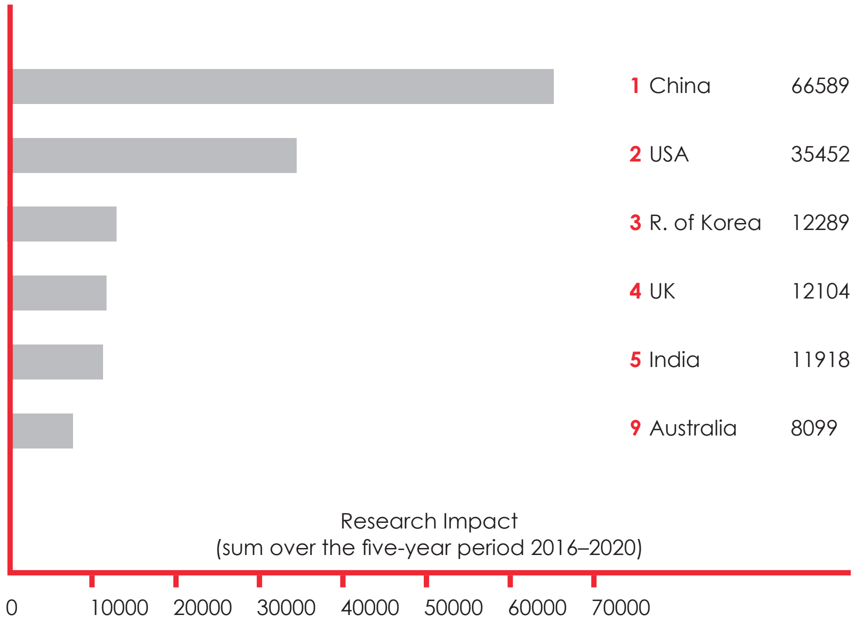
Diversifying our export mix to include hydrogen and ammonia as a source of fuel and power for current and emerging markets may help reduce Australia's reliance on traditional natural resources, such as coal. This could build Australia's economic resilience to price fluctuations and geopolitical actions which may not be in Australia's economic interests. Production of hydrogen and ammonia as clean, alternative sources of power may adversely affect other Australia exports, most notably coal. It may also affect other exports such as liquefied natural gas, which is a current source of (non-clean) hydrogen fuel.

Domestic commercialisation of hydrogen and ammonia is dependent on the competitiveness of energy pricing, especially as non-renewable power sources currently provide lower electricity generation costs. Furthermore, Australia's electricity grid has not yet been adapted to generate power from hydrogen or ammonia. Further investment in our capabilities, as well as adaption of the electricity grid, is required to lower costs, encourage domestic consumption and increase the competitiveness of Australian-sourced hydrogen. There is also further opportunity to alleviate national security and energy risks through the decentralisation of power production and increased source diversity.

As alternative fuels are increasingly adopted as sources for heat and electricity, countries may use hydrogen, for example, as a strategic, geopolitical asset. Attempts to undermine the use or export of hydrogen may create both an economic and strategic risk for Australia – particularly if Australia seeks to position itself as a key regional supplier of hydrogen. However, this risk can be mitigated through the reinforcement and facilitation of free trade, as well as export to a variety of trading partners and markets.

Research Impact (RI)

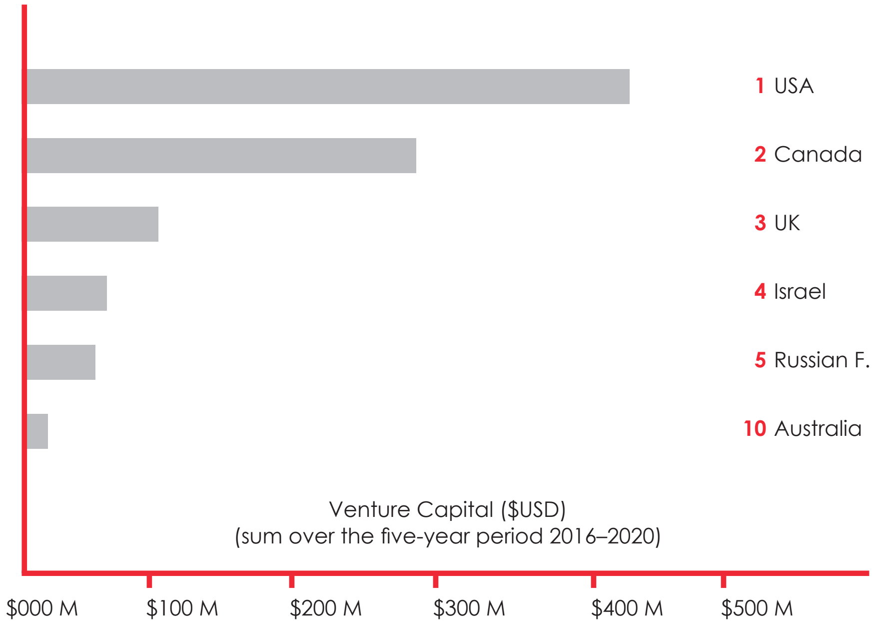
China has the highest research impact well ahead of the United States, with Australia ranked 9th. Total volume of published research has decreased at around 1% p.a. over the five-year period 2016–2020, with 25% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

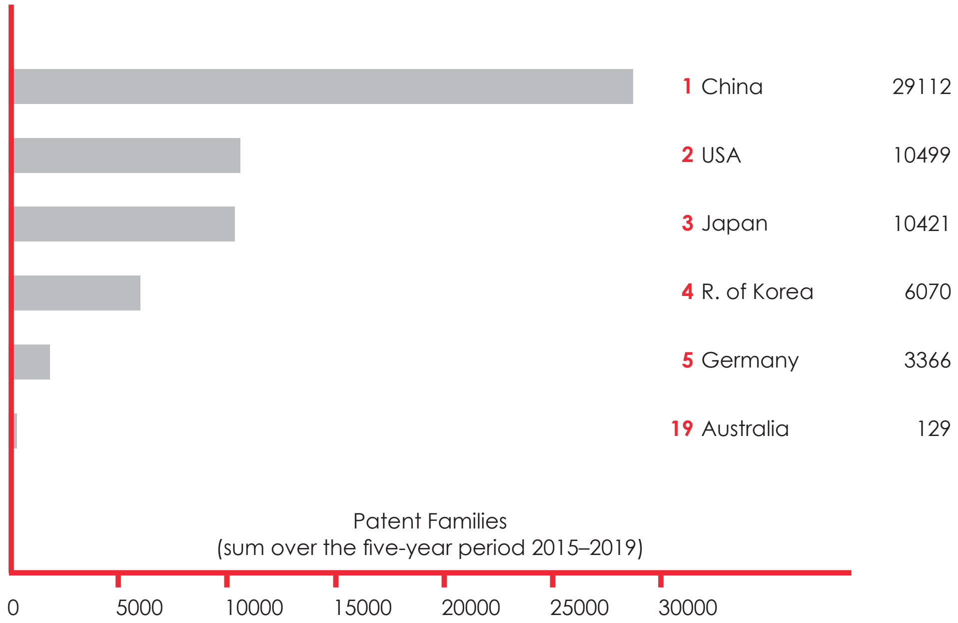
The United States has the highest venture capital (VC) investment, ahead of Canada and the United Kingdom. Australia is ranked 10th for VC investment in this area. Investment in this area has been growing at 28% p.a. since 2016.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

Most patents for this technology were filed by Chinese applicants or inventors, with almost three times the number of the United States. Overall patent applications have been increasing at 3% annually since 2015. Australia ranks 19th.



Research Institutions – International

China dominates the top international institutions with 6 in the top 10. The United States, France and Malaysia make up the remainder of the top 10 international institutions.

Rank	Top International Institution	Research Impact
1	Chinese Academy of Sciences | China	8742
2	United States Department of Energy | United States	4504
3	French National Centre for Scientific Research (CNRS) | France	4297
4	Tianjin University | China	3934
5	Tsinghua University | China	3847
6	University of Science and Technology of China | China	3447
7	Argonne National Laboratory | United States	2953
8	Universiti Kebangsaan Malaysia | Malaysia	2547
9	Harbin Institute of Technology | China	2479
10	University of Chinese Academy of Sciences | China	2459

Research Institutions – Australia

Within Australia, the University of New South Wales leads research impact, and is ranked 18th internationally. Second ranked Curtin University ranks 35th internationally.

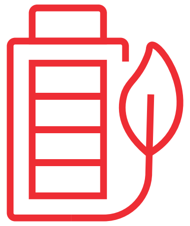
Rank	Top Australian Institution	Research Impact
1	University of New South Wales	2130
2	Curtin University	1600
3	University of Queensland	847
4	Royal Melbourne Institute of Technology University	675
5	Monash University	558
6	Swinburne University of Technology	455
7	University of Technology Sydney	358
8	Deakin University	283
9	University of Wollongong	280
10	University of Sydney	211

Patents – Australia

Top 5 Australian Patent Applicants	Patent Families
NewSouth Innovations	9
CSIRO	7
Aquahydrex	3
Hydrexia	3
Kohodo Hyrdrogen Energy	3

Patents filed by Australian businesses, 2015–2019.

Photovoltaics



Devices that convert solar energy into electricity using layers of semiconductor materials.

Key Sectors

Impacts all sectors, including:

- Agriculture, Forestry and Fishing
- Banking and Finance
- Communications
- Construction
- Defence and Defence Industry
- Energy and Environment
- Health
- Manufacturing
- Mining and Resources
- Space
- Transport and Logistics

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security	X		

Key Australian Government Actions

Initiatives

- Australian Renewable Energy Agency (ARENA)
- Clean Energy Finance Corporation (CEFC)
- Emissions Reduction Fund
- Energy Reporting Scheme
- Australian National Registry of Emissions Units (ANREU)
- Large-scale Renewable Energy Target
- Small-scale Renewable Energy Scheme
- Kidston Pumper Hydro Energy Storage

Regulations

- Clean Energy Regulator Act 2011

Example Outcomes

- Diversified electricity grid and energy supply
- Improved access to cheap, effective renewable energy and increased uptake in solar technology
- Capability to power remote devices without the need for centralised electricity
- Direct powering of electric vehicles
- Financial benefits to consumers from self-generation of solar power
- Financial benefits to agricultural producers from biodiversity stewardship options
- Improved water management in arid areas using floating solar farms

Underpinning Science

ANZ Standard Research Classification

- Electronics, sensors and digital hardware
- Electrical engineering
- Materials engineering

Example Applications

Readiness Level – Now

- Rooftop solar PV systems for homes and businesses
- Large scale solar farms
- Silicon PV cells integrated into building cladding and roof tiles
- Solar-powered un-crewed aerial vehicles with extended endurance
- Solar-powered spacecraft and the international space station powered by solar arrays
- Floatvoltaics – floating solar panels placed on bodies of water, estimated to be 8-10% more efficient than land-based variants

Readiness Level – 2–5 years

- Third generation perovskite solar cells that generate 30% more electricity than conventional solar cells
- Solar sail technology for low-cost deep space missions
- Solar skins – allows for the custom display of images by allowing light to filter through a panel
- Solar fabrics – fabrics that can be bent or glued on any surface and are ten times lighter than framed panels

Readiness Level – Beyond 5 years

- Transparent quantum dot or organic PV cells integrated into windows and skylights
- Highly efficient photovoltaic/thermal systems that convert sunlight into electricity and also store the excess thermal energy produced
- Indoor photovoltaics to power internet of things devices from ambient light inside buildings

Australia's place in the world

Australia ranks 7th for research impact, led by the Australian National University in 4th place internationally. Australia also has 3 other research institutions ranked in the world's top 50. China leads research and has 4 research institutions in the top 10, followed by the United States in 2nd place. Australia has 2 institutions in the international top 10 institutions for research impact.

Venture capital (VC) investment in photovoltaics has been increasing at around 5% p.a. since 2016, with the United States having significant amounts of VC investment, well ahead of Norway, Canada, Germany and France, while Australia is ranked 15th. Australia is also ranked 15th for patents for photovoltaics, which is led by China with approximately 2.5 times the number of patents compared to 2nd ranked United States.

Given the abundance of solar radiation throughout Australia, we have a competitive advantage in this area, particularly since we have world-leading research and are an attractive destination for capital investment. As photovoltaic cells become cheaper and more efficient, Australia could compete more effectively for energy intensive industry and advanced manufacturing including food, iron, steel, aluminium, paper and chemical production. PV can also support other key technologies such as hydrogen production.

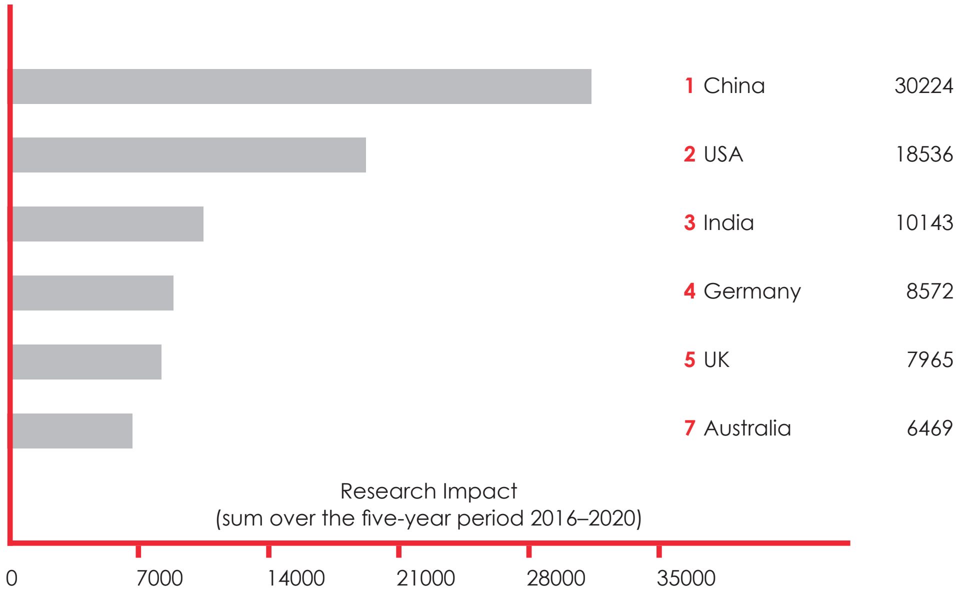
Opportunities and Risks

Photovoltaic (PV) technology presents Australia with enormous opportunities and harnessing PV could provide Australia with a cost-effective way to meet our emission reduction targets. In 2021, Australia committed to a national goal of net zero emissions by 2050 ahead of the 2021 UN Climate Change Conference (COP26) in Glasgow. One key technology expected to help Australia reach net zero emissions is 'ultra-low-cost solar'. Australia is ideally placed to meet our emissions commitments through PV using our environmental advantages, leveraging our strong research sector and supporting pathways for venture capital investment. Investment in solar power is becoming increasingly affordable, both for households and on a broader scale. Australia has the highest solar radiation per unit area of any continent, giving us abundant supplies of renewable energy. Specifically, producing solar panels more efficiently through further innovation in quantum dot cells could result in order-of-magnitude reductions in greenhouse-gas emissions. In 2020–21, Solar PV generated approximately 10% of Australia's electricity and remains the fastest growing generation type in Australia.

Despite Australia's advantages in this area challenges remain, in particular, domestically, the best solar resources are in parts of Australia with the least electricity network coverage, hence the need for increased electricity transmission capability. Since PV electricity production is inherently linked with the availability of sunlight, supply fluctuates with the weather and time-of-day. In order to facilitate a stable supply of PV generated electricity to the grid, sophisticated (and as yet undeveloped) technology is required. Storage of renewable energy (including PV) remains expensive for both battery creation and storage costs, however this cost is expected to decrease as these technologies advance. The manufacture and disposal of solar panels is an additional environmental concern, however there is increasing focus on developing end of life disposal and management to combat this issue. To fully leverage the benefits offered by PV, Australia needs to advance complementary technologies and policies associated with supply, storage, manufacturing and disposal concerns.

Research Impact (RI)

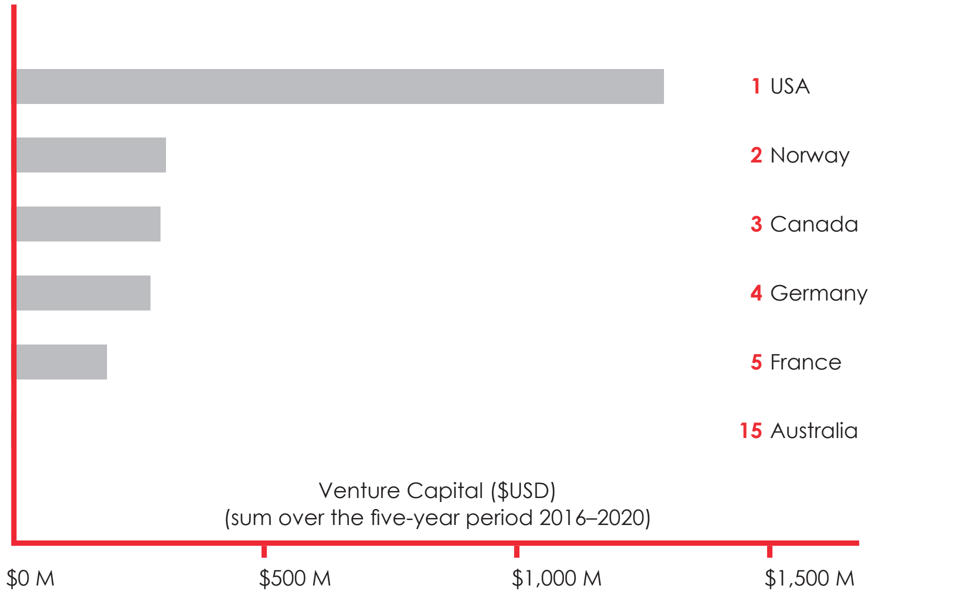
China has the highest research impact in this area, ahead of the United States. Australia is ranked 7th. Total volume of published research has been increasing at 7% p.a. over the 5 year period 2016–2020, with 27% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

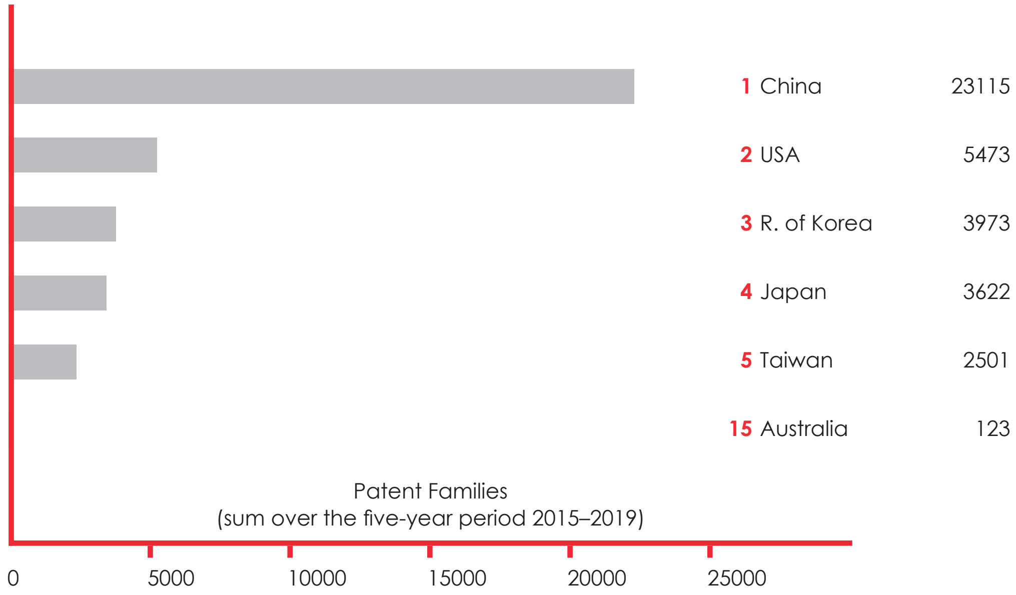
The United States has significantly higher amounts of VC investment, well ahead of Norway, Canada, Germany and France, while Australia is ranked 15th for VC investment in photovoltaics. Investment in this area has been growing at 5% p.a. since 2016.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents - International

The number of patents being lodged annually in this field has been decreasing by around 1% p.a. since 2015. Most patents in this field were filed by applicants or inventors from China. Australia is ranked 15th.



Research Institutions - International

China has 4 institutions in the top 10 international institutions, and Australia has two. Institutions from France, Germany, the United States and the United Kingdom make up the remainder of the top 10.

Rank	Top International Institution	Research Impact
1	Chinese Academy of Sciences | China	6227
2	French National Centre for Scientific Research (CNRS) | France	2968
3	Helmholtz Centre Berlin for Materials and Energy | Germany	2931
4	Australian National University | Australia	2677
5	National Renewable Energy Laboratory | United States	2473
6	University of New South Wales | Australia	2459
7	University of Chinese Academy of Sciences | China	2284
8	University of Oxford | United Kingdom	2225
9	Peking University | China	2152
10	Huazhong University of Science and Technology | China	2101

Research Institutions - Australia

The top 4 ranked Australian institutions are ranked in the top 50 international institutions for research impact. The top ranked Australian National University is ranked 4th internationally, and the University of New South Wales is ranked 6th internationally.

Rank	Top Australian Institution	Research Impact
1	Australian National University	2677
2	University of New South Wales	2459
3	University of Melbourne	1578
4	Monash University	866
5	University of Sydney	418
6	Swinburne University of Technology	370
7	Royal Melbourne Institute of Technology University	355
8	University of Queensland	345
9	University of Western Australia	334
10	Queensland University of Technology	304

Patents - Australia

Top Australian Patent Applicants	Patent Families
NewSouth Innovations	26
CSIRO	5
Australian National University	4
Clearvue Tech Ltd	3
A number of Australian businesses have less than 3 patent families recorded in this technology area	

Patents filed by Australian businesses, 2015–2019.

Data current as at 16 March 2022.

Supercapacitors

Electrochemical devices that can store large amounts of energy in small volumes. Supercapacitors store less energy and for shorter durations than rechargeable batteries (hours or days, rather than months or years), but can accept and deliver charge much faster than rechargeable batteries, and tolerate many more discharge cycles than rechargeable batteries before performance degrades.

Key Sectors

Impacts all sectors, including:

- Agriculture, Forestry and Fishing
- Communications
- Construction
- Defence & Defence Industry
- Energy
- Health
- Manufacturing
- Mining & Resources
- Space
- Transport & Logistics

Estimated impact on national interest	Low	Med	High
Economic Prosperity		X	
National Security		X	

Key Australian Government Actions

Initiatives

- CSIRO Centre for Hybrid Energy Systems
- CSIRO Stored Energy Integration Facility
- Project Rail – Rail Manufacturing Cooperative Research Centre
- Low Emissions Technology Statement
- Australian Research Council Training Centre for Future Energy Storage Technologies

Regulations

- Defence and Strategic Goods List 2021

Example Outcomes

- Increased renewable electricity reliability and competitiveness from supercapacitor enabled storage systems
- Significant reduction in battery waste from longer lifecycles and reduced source materials
- More convenient electric vehicles through reducing charging time from hours to minutes
- Improved mobility of computing devices through greater recharging capacity
- More comprehensive computer backup solutions which store the contents of caches and other Static Random-Access Memory (SRAM)

Underpinning Science

ANZ Standard Research Classification

- Electrical engineering
- Electronics, sensors and digital hardware
- Materials engineering
- Physical chemistry

Example Applications

Readiness Level – Now

- Regenerative braking systems for vehicles and elevators
- Computer memory backup
- Starters for diesel train engines
- Electricity grid stabilisation
- Rapid charging stations for electric buses
- Flash on mobile phones
- Used in combination with lead-acid batteries, such as CSIRO-developed Ultrabattery®

Readiness Level – 2–5 years

- Ultra-thin, flexible supercapacitors to power wearable electronic devices
- Hybrid supercapacitor batteries that can fully charge in a matter of seconds
- Battery-free IoT devices using a combination of solar energy harvesting and high-powered supercapacitors

Readiness Level – Beyond 5 years

- Transparent energy storage devices for "invisible" electronics

Australia's place in the world

China ranks 1st and has 9 of the top 10 research institutions internationally, with the United States a distant 2nd. The total quantity of research is growing rapidly, with 41% p.a. increase over the 2016–2020 period. Australia ranks 5th for research impact, led by the University of Wollongong, which ranks 34th internationally. The United States is ranked first for venture capital (VC) investment, followed by Estonia and Canada; Australia is unranked. VC investment in supercapacitors has been increasing by 35% p.a. since 2016. Globally, the number of new patents being lodged has been decreasing by around 1% since 2015, with China having the greatest number of patents lodged. Japan is ranked 2nd for patents, and Australia is 12th.

As a major energy producer and exporter, there are opportunities to enhance our competitive advantage in this field. We are well situated and increasingly connected to major partner nations to leverage our research skill and to maximise commercial opportunities from the effective development and implementation of this technology.

Opportunities and Risks

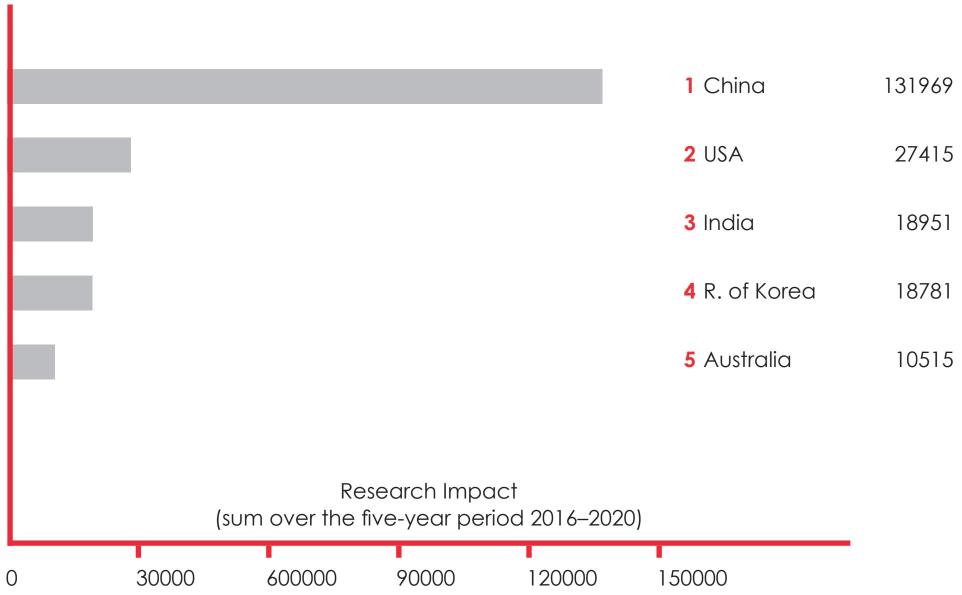
Supercapacitors have the potential to enable more reliable and efficient consumer electronics, benefiting all Australians. In particular, as Australia produces more renewable energy and the grid is subject to bursts or deficits of power, supercapacitors may have a potential role to play in helping smooth the impact on the grid through rapid charging ability in conjunction with traditional batteries.

Supercapacitors also promise to be greener than existing sources of energy storage, thereby enhancing Australia's green capability and credentials, by improving the longevity and efficiency of batteries, and from use in small devices. They are also more stable at lower temperatures, making them useful in a broader range of environments.

As high energy supercapacitors are still an emerging technology, there are various risks associated with them. As the technology continues to be too expensive for mass consumption, this may dampen its potential benefits and lessen the return on investment for Australian research. A further risk is that industry standards surrounding the implementation of the product are not developed in a timely manner, creating long term inefficiencies from various competing standards for implementing and utilising the technology.

Research Impact (RI)

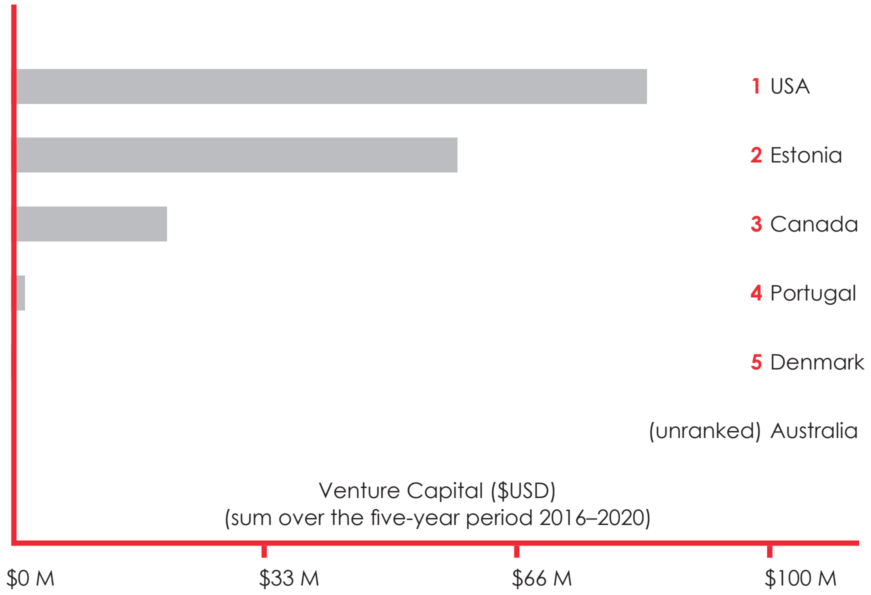
China has the highest research impact in this area, ahead of the United States. Australia is ranked 5th. Total volume of published research has been increasing at 41% p.a. over the 5 year period 2016–2020, with 23% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

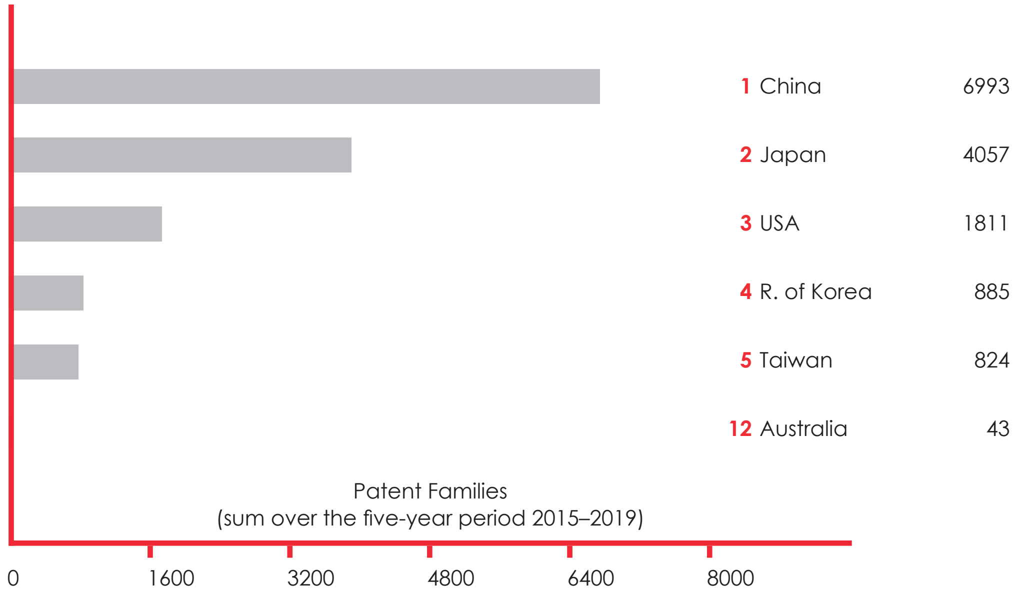
The United States has the greatest amount of VC investment in supercapacitors, ahead of Estonia and Canada, while Australia is unranked. Investment in this area has been growing at 35% p.a. since 2016.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents - International

The number of patents being lodged annually in this field has been decreasing by around 1% since 2015. Most patents in this field were filed by applicants or inventors from China. Australia is ranked 12th.



Research Institutions - International

China has 9 of the global top 10 institutions. Singapore is the only other country with an institution in the top 10.

Rank	Top International Institution	Research Impact
1	Chinese Academy of Sciences | China	14560
2	University of Chinese Academy of Sciences | China	4537
3	Harbin Institute of Technology | China	4193
4	Tsinghua University | China	4097
5	Chongqing University | China	3871
6	Nanyang Technological University | Singapore	3312
7	Beijing University of Chemical Technology | China	3289
8	Peking University | China	3244
9	Tianjin University | China	3194
10	Yangzhou University | China	3193

Research Institutions - Australia

Within Australia, the University of Wollongong has the highest research impact, and is ranked 34th internationally.

Rank	Top Australian Institution	Research Impact
1	University of Wollongong	2086
2	University of Queensland	1622
3	University of New South Wales	1520
4	Deakin University	1513
5	Queensland University of Technology	1070
6	University of Adelaide	1017
7	Swinburne University of Technology	1015
8	University of Melbourne	991
9	Australian National University	898
10	University of Sydney	855

Patents - Australia

Top Australian Patent Applicants	Patent Families
Monash University	4
Deakin University	3
Anteo Tech	2
Gelion Technologies	2
NewSouth Innovations	2

Patents filed by Australian businesses, 2015–2019.

Data current as at 16 March 2022.

Australian Government

CTPCO
CRITICAL TECHNOLOGIES POLICY COORDINATION OFFICE

Post-Quantum cryptography

Mathematical techniques for ensuring that information stays private, or is authentic, that resist attacks by both quantum and non-quantum (i.e. classical) computers. The leading application for post-quantum cryptography is securing online communications against attacks using quantum computers.

Key Sectors

Influences all sectors of the economy, including:

- Government
- Agriculture
- Banking & Finance
- Communications
- Defence & Defence Industry
- Energy & Environment
- Health
- Transport & Logistics
- Education & Research
- Mining & Resources
- Manufacturing
- Space

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security			X

Key Australian Government Actions

Initiatives

- Australian Cyber Security Centre (ACSC)
- The ARC Centre of Excellence for Quantum Computation and Communication Technology
- Next Generation Technologies Fund
- Silicon Quantum Computing
- Quantum Technology Roadmap
- Digital Economy and Technology Policy
- Australian Cyber Security Growth Network

Regulations

- Defence and Strategic Goods List 2021

Example Outcomes

- Sensitive information communicated before practical quantum computers become available are protected from future advancements in quantum computing
- E-commerce, internet banking, secure software distribution and other applications that depend on public-key cryptography and use post-quantum cryptography are not adversely affected by advancements in quantum computing

Underpinning Science

ANZ Standard Research Classification Category

- Applied Mathematics
- Mathematical Physics
- Numerical and Computational Mathematics
- Software Engineering
- Data Management and Data Science
- Theory of Computation
- Electronics, Sensors and Digital Hardware
- Mechanical Engineering
- Electrical Engineering
- Optical Physics
- Quantum Physics
- Electronics, Sensors and Digital Hardware

Example Applications

Readiness Level – Now

- Implementation of pre-standardised post-quantum cryptography for classified networks
- Cyber security companies providing pre-standardised post-quantum cryptography services
- Laboratory testing of hardware accelerators for pre-standardisation post-quantum cryptographic algorithms

Readiness Level – 2–5 years

- Early adopters in the commercial sector (e.g. financial institutions) may implement post-quantum cryptography for critical networks

Readiness Level - Beyond 5 years

- Post-quantum cryptographic algorithms are incorporated in all consumer, commercial and industrial devices and software that need to store, send or receive sensitive information
- Dedicated hardware for increasing the speed of post-quantum cryptography

Australia's place in the world

The United States leads public research in post-quantum cryptography, with the highest research impact and two of the top ten institutions. Seven of the top ten institutions are based in the European Union, with Netherlands alone holding three. Australia is ranked 19th for research impact. Given the sensitive nature of this technology much cutting-edge research is unlikely to be in the public domain, meaning this assessment may not be a true reflection of overall research capability. This assumption is also supported by the limited patent activity in this area, which is led by the United State, followed closely by China. Australia has no patents in this area. The United Kingdom has the highest amount of venture capital (VC) investment in this area, ahead of Canada and the United States.

Opportunities and Risks

Post-quantum cryptography provides assurance that advances in quantum computing will not adversely affect the confidentiality and authenticity of digital communications and information, which currently use methods that are theoretically vulnerable to attacks using practical quantum computing.

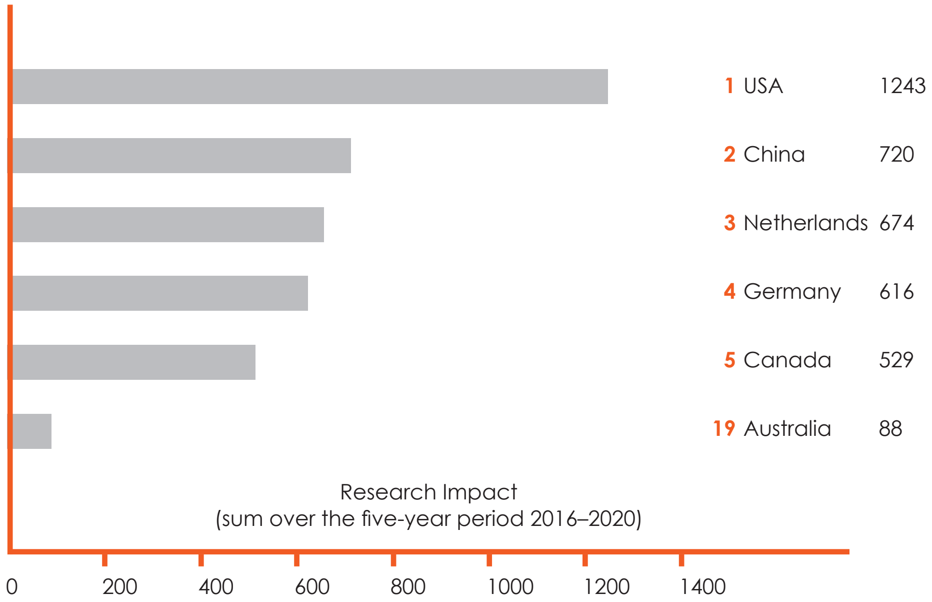
The opportunity offered by post-quantum cryptography is that Australians can continue to use their digital devices to communicate sensitive information with confidence that what is private today will stay private in the future. This applies to both government communications and communications between businesses and individuals. Subject to appropriate safeguards, Australia can also potentially export post-quantum cryptography hardware and software implementations.

Australia must have domestic expertise in PQC to ensure that we can usefully contribute to international efforts to develop suitable systems and to provide expertise in the deployment and testing of these technologies locally. Assuming that practical quantum computing is achievable, Australia faces risks to security until appropriately secure post-quantum cryptography is available to government, businesses and individuals. Because malicious actors can intercept and store encrypted communications today for decryption by a future practical quantum computer, the security risks increase the longer it takes to develop and deploy appropriately secure post-quantum cryptography. Australia also faces economic risks if our trading partners do not also have access to appropriately secure (and compatible) post-quantum cryptography, as that would limit the security of digital trade and ecommerce.

The transition to post-quantum cryptography will also require significant updates to current cryptography, which will take significant time and money, and require hardware as well as software updates. This transition could give rise to additional risks and it is foreseeable that many existing and legacy systems may never be updated and remain vulnerable until they are retired.

Research Impact (RI)

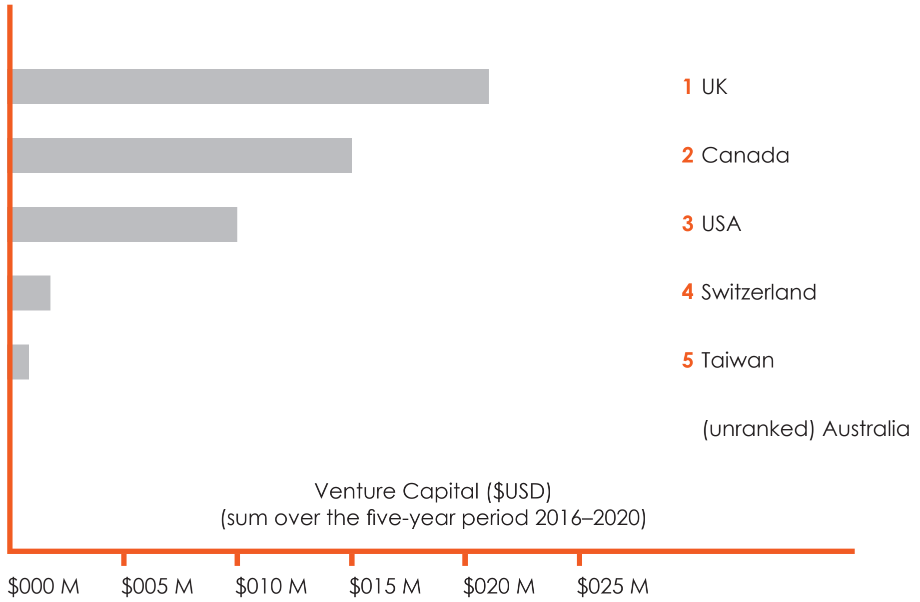
The United States has the highest research impact, with Australia ranked 19th. Total volume of published research has increased at around 33% p.a. over the 5 year period 2016–2020, with 31% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality

VC Investment

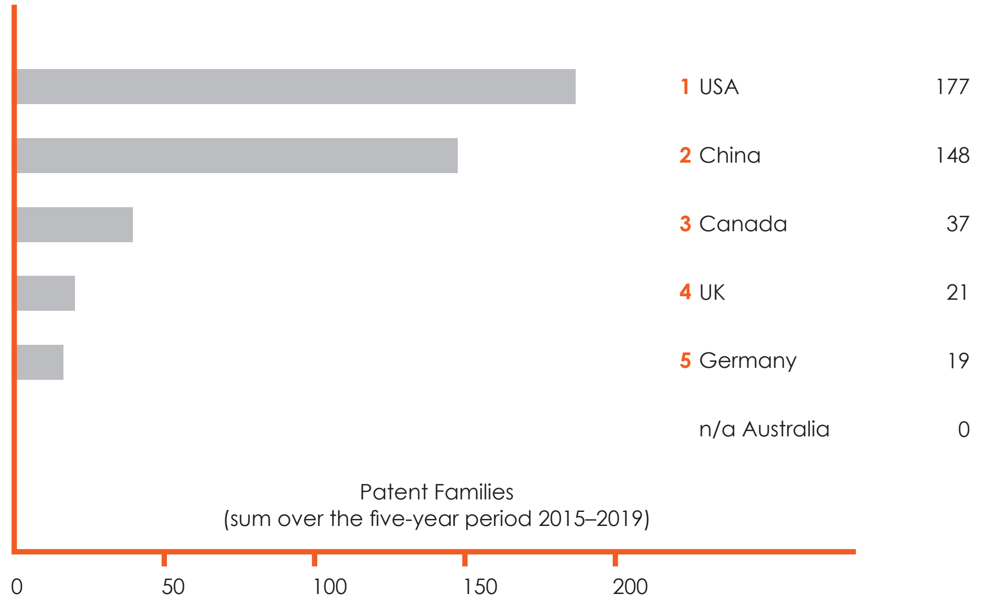
The United Kingdom has the highest venture capital (VC) investment in post quantum cryptography, ahead of Canada and the United States. Australia is unranked for VC investment in this area. Globally VC investment into post-quantum cryptography has increased by around 37% over the past 5 years.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

Most patents for this technology were filed by applicants or inventors in the United States, slightly more than Chinese applicants or inventors. Overall patent applications have been increasing at 40% annually since 2015. There have been no patent filings originating from Australia for this technology.



Research Institutions – International

The European Union has 7 of the top 10 international institutions for research impact, with Netherlands alone holding 3. The United States has 2 institutions.

Rank	Top International Institution	Research Impact
1	Radboud University Nijmegen | Netherlands	382
2	University of Waterloo | Canada	327
3	Eindhoven University of Technology | Netherlands	259
4	Microsoft USA | United States	257
5	Centrum voor Wiskunde en Informatica | Netherlands	253
6	Florida Atlantic University | United States	198
7	French National Centre for Scientific Research (CNRS) | France	195
8	Institut national de recherche en informatique et en automatique | France	165
9	Ruhr University Bochum | Germany	155
10	Technische Universität Darmstadt | Germany	151

Research Institutions – Australia

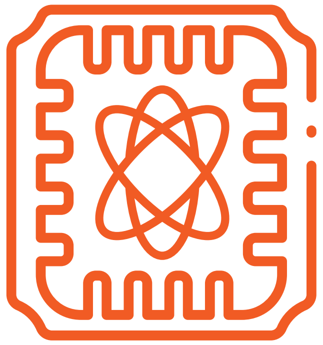
Australia has limited research capability in this area, based on the research impact derived from publically available information. Monash University has the highest research impact, but there are no institutes in the top 50. Only 8 Australian institutes had publically available information to calculate research impact.

Rank	Top Australian Institution	Research Impact
1	Monash University	44
2	University of Wollongong	20
3	University of Adelaide	15
4	CSIRO	8
5	Queensland University of Technology	6
6	Swinburne University of Technology	2
7	University of Technology Sydney	2
8	University of New South Wales	1

Patents – Australia

There are no patents filed in Australia by Australian applicants identified for this technology.

Quantum Communications



Devices and systems that communicate quantum information at a distance, including cryptographic keys. Applications for quantum communications include transferring information between quantum computers and sharing cryptographic keys (which are like secret passwords) between distant people in a way that means it is impossible for anyone else to copy.

Key Australian Government Actions

Initiatives

- Quantum Technology Roadmap
- Australian Cyber Security Growth Network
- The ARC Centre of Excellence for Quantum Computation and Communication Technology
- Next Generation Technologies Fund
- Silicon Quantum Computing
- Digital economy and technology policy

Regulations

- Defence and Strategic Goods List 2021

Example Outcomes

- Communicating quantum information between remote sites
- Secure cryptographic key exchange between strangers

Underpinning Science

ANZ Standard Research Classification Category

- Applied mathematics
- Mathematical physics
- Numerical and computational mathematics
- Software engineering
- Data management and data science
- Theory of computation
- Electronics, sensors and digital hardware
- Mechanical engineering
- Electrical engineering
- Optical physics
- Quantum physics
- Electronics, sensors and digital hardware

Example Applications

Readiness Level – Now

- Technical demonstration of quantum key distribution between remote sites

Readiness Level – 2–5 years

- Technical demonstration of quantum key distribution between remote sites

Readiness Level – Beyond 5 years

- Large-scale testing of a secure quantum key distribution network
- Quantum networks to enhance the computing capability of quantum computers
- Blind quantum computing which will allow users across the globe to securely and remotely access quantum computers to run calculations without disclosing the calculations or results

Key Sectors

- Defence Industry
- Intelligence
- Communications
- Banking & Finance

Estimated impact on national interest	Low	Med	High
Economic Prosperity		X	
National Security		X	

Australia's place in the world

China has the highest research impact in this area and has 4 of the global top 10 institutions, well ahead of the United States, which is ranked 2nd and only has 1 institute in the international top 10 institutions. Australia ranks 7th globally for research impact in this field, led by the University of Technology Sydney, which is ranked 6th internationally. The United States leads venture capital (VC) investment in this area, followed by the United Kingdom and Canada; Australia has the 9th highest VC investment. China has the greatest number of patents in this area, with more than three times as many patents as the United States, in second place; Australia ranks 23rd with 6 patents.

Australia ranks highly in this field with significant expertise in the development of quantum communications technology, and was an early leader in the development and commercialisation of quantum technologies for secure communication. The Australian Research Council Centres of Excellence program, university, and private sector investment facilitate much of Australia's research on quantum. The Australian Government's investment in overall quantum technology research, including quantum communications, was AU$195 million in 2020.

Opportunities and Risks

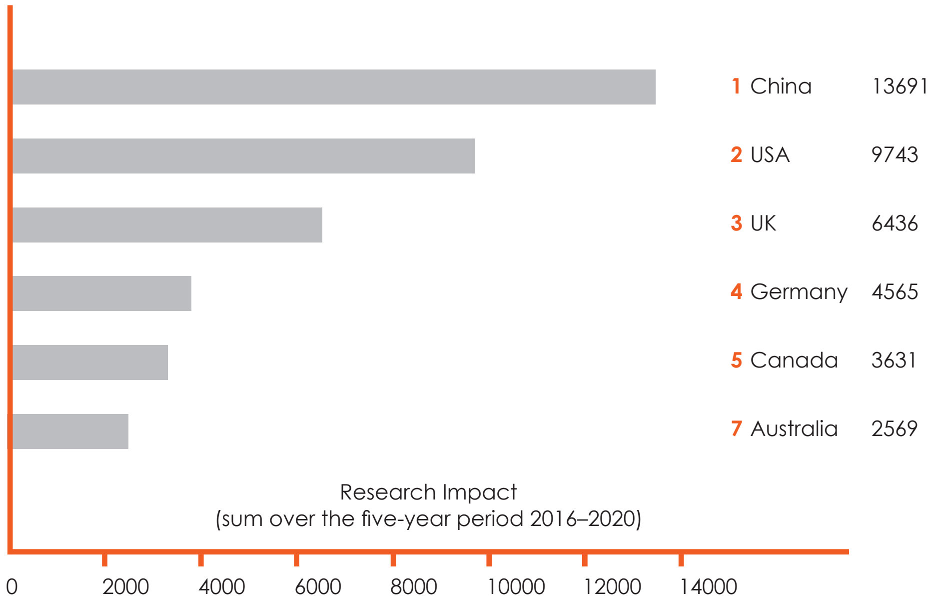
Quantum communications promises to enable the transfer of information in quantum states, rather than in the digital form of most modern communications technologies. This will enable communications between quantum computers and other quantum systems, which can save time and fidelity by communicating quantum information directly, rather than by conversion to a digital form. Quantum communications also power quantum key distribution (QKD), which exploits the inherent properties of quantum mechanics to detect efforts to intercept or eavesdrop on people exchanging cryptographic (with users reverting to non-quantum communications technologies once the keys are exchanged).

Noting the importance of quantum technologies in global political and security considerations, Australia's increased quantum capabilities and research may also bring with it security risks stemming from geopolitical importance of quantum technologies. Risks could include foreign interference and the unwanted transfer of quantum research and technologies, IP theft, and espionage on Australia's defence quantum communications and technological capabilities. It has been suggested that quantum communications may introduce new potential avenues for attack, such as physically interrupting satellite-based quantum key distribution using high-power ground-based lasers.

It is likely that impractical and expensive hardware and limited real-world use cases may make quantum key distribution unsuitable for future challenges, and that it will be superseded by post-quantum cryptography before it is established.

Research Impact (RI)

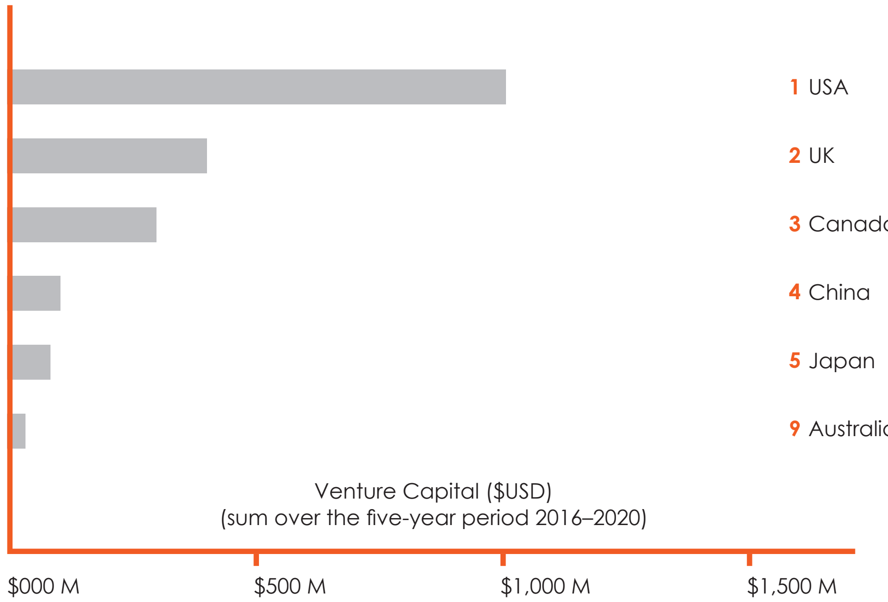
China leads research impact in this area, with Australia ranked 7th. Total volume of published research has increased at around 10% p.a. over the 5 year period 2016–2020, with 28% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

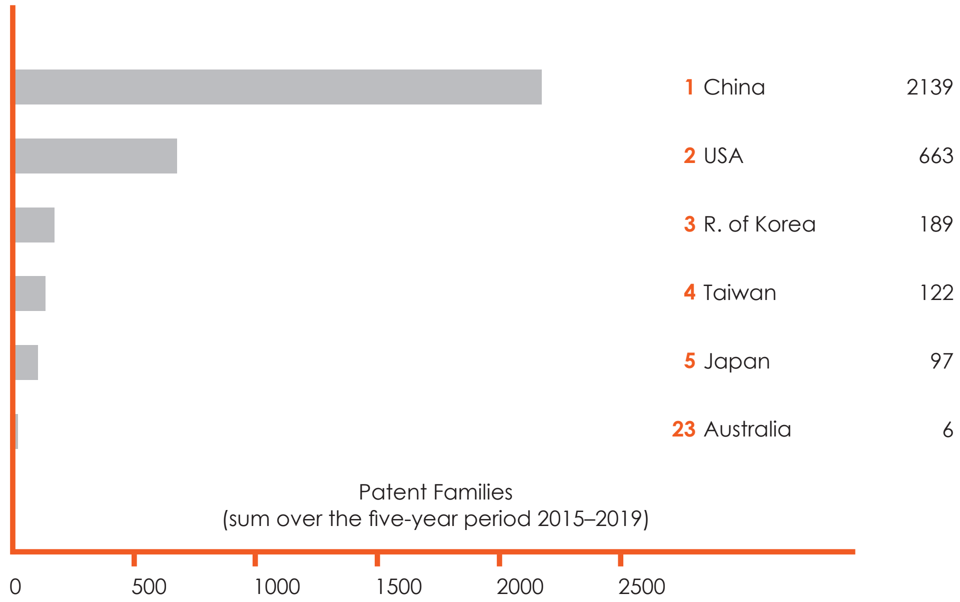
The United States has the highest venture capital (VC) investment for quantum communications, with Australia ranked 9th. Investment in this area has been increasing at around 26% p.a.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

The highest number of patents for this technology were filed by Chinese applicants or inventors, more than three times the number of the United States. Overall patent applications have been increasing at 30% annually since 2015



Research Institutions – International

China has 4 of the top 10 research institutions, including the top three. There are a number of European institutes in the top 10.

Rank	Top International Institution	Research Impact
1	University of Science and Technology of China | China	4287
2	Chinese Academy of Sciences | China	3966
3	Tsinghua University | China	1758
4	French National Centre for Scientific Research (CNRS) | France	1546
5	Delft University of Technology | Netherlands	1462
6	University of Technology Sydney | Australia	1432
7	Austrian Academy of Sciences | Austria	1408
8	Massachusetts Institute of Technology | United States	1190
9	Peking University | China	1130
10	University of Waterloo | Canada	1126

Research Institutions – Australia

Within Australia, the University of Technology Sydney has the highest research metric, which places it 6th compared to the top international institutions. All of the top 6 Australian universities are ranked in the top 50 international institutions.

Rank	Top Australian Institution	Research Impact
1	University of Technology Sydney	1432
2	Australian National University	924
3	Royal Melbourne Institute of Technology University	844
4	University of New South Wales	715
5	Griffith University Queensland	694
6	University of Melbourne	662
7	University of Sydney	492
8	University of Queensland	183
9	Macquarie University	164
10	University of Western Australia	129

Patents – Australia

All Australian patents in this area are held by private citizens.

Quantum Sensors

Devices that depend directly on quantum mechanical properties and effects for high precision and high sensitivity measurements. Applications for quantum sensors include enhanced imaging, GPS-free navigation and remote sensing.

Key Sectors

- Agriculture
- Defence & Defence Industry
- Energy & Environment
- Health
- Construction
- Manufacturing
- Transport & Logistics
- Mining & Resources

Estimated impact on national interest	Low	Med	High
Economic Prosperity		X	
National Security			X

Key Australian Government Actions

Initiatives

- Quantum Technology Roadmap
- Quantum-Assured Position, Navigation and Timing (PNT) DSTG star-shot
- Silicon Quantum Computing
- Next Generation Technologies Fund
- Digital Economy and Technology Policy

Regulations

- Defence and Strategic Goods List 2021

Example Outcomes

- Enhanced capabilities for the early detection of diseased tissue states
- Detect small signals of interest including magnetic anomalies and trace chemicals
- Easier discovery of valuable ore deposits and efficient groundwater monitoring
- Precision positioning, navigation and timing (PNT) in Global Positioning System (GPS) - denied environments such as underground or underwater
- Early-warning systems for volcanic eruptions and earthquakes
- Mapping of the magnetic field inside the brain, which may be used to identify and treat brain injuries or neurological conditions
- Improved remote sensing capabilities, enabling better detection of submarines and stealth aircraft
- Use of quantum sensors for analysis of organic structures (e.g. medical diagnosis)

Underpinning Science

ANZ Standard Research Classification Category

- Applied Mathematics
- Mathematical Physics
- Numerical and Computational Mathematics
- Software Engineering
- Data Management and Data Science
- Theory of Computation
- Electronics, Sensors and Digital Hardware
- Mechanical Engineering
- Electrical Engineering
- Optical Physics
- Quantum Physics
- Macromolecular and Materials Chemistry
- Communications Engineering
- Electronics, Sensors and Digital Hardware

Example Applications

Readiness Level – Now

- Magnetic geophysical surveying for mining, archaeology and unexploded ordnance detection
- Radiofrequency testing equipment for measuring performance of wireless communication devices
- Communications, radar and GPS synchronisation using atomic clocks

Readiness Level – 2–5 years

- Compact medical diagnostic devices
- Magnetic anomaly detection of submarines, mines and underground infrastructure
- GPS-free navigation based on magnetic and gravitational anomaly maps
- Improved radar and communications using atomic antennas
- Covert signals intelligence collection using atomic antennas

Readiness Level – Beyond 5 years

- Quantum lidar for autonomous vehicles and surveying
- Quantum radar for advanced military radar systems
- Sensing and use of THz signals for next generation communications

Australia's place in the world

The United States has the highest research impact for quantum sensors, and has the top 2 institutes internationally. Australia is ranked 16th for research impact, and the Australian National University is ranked 45th internationally. Australia is ranked 3rd for venture capital (VC) investment for quantum sensors, behind the United States and the United Kingdom. China has the highest number of patents in this area, ahead of the United States (2nd) and Japan (3rd).

Behind the United States and China, Japan also has considerable strengths in this area and is ranked 3rd for research impact and patents, and 4th for VC investment. There are 3 Japanese institutes in the international top 10 institutions.

Opportunities and Risks

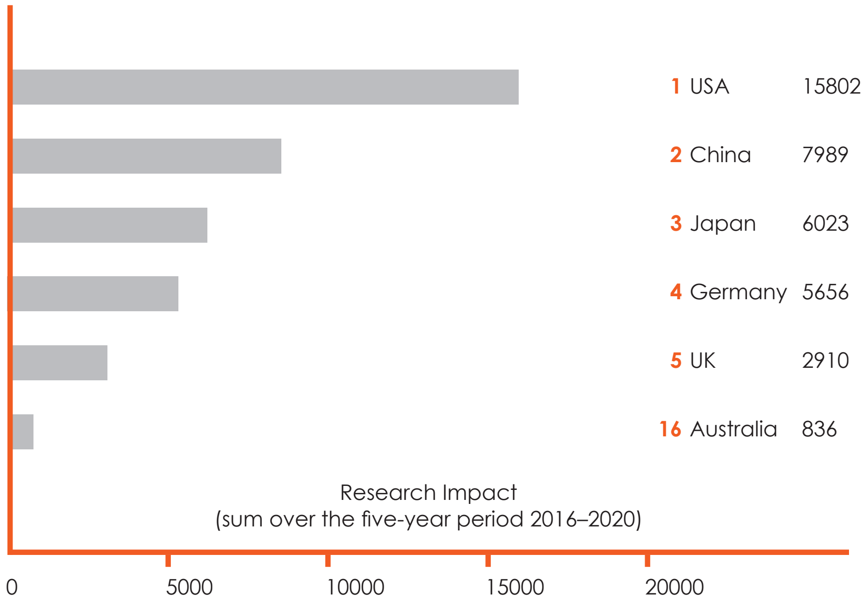
Quantum sensors present a wealth of opportunities for Australia. By exploiting the inherent sensitivity of quantum states, quantum sensors can detect changes in the physical environment faster, more precisely and/or with higher sensitivity. The CSIRO report, Growing Australia's Quantum Technology Industry, forecast that Australia could generate $940 million in revenue if it could capture 5% of the estimated addressable market for quantum-enhanced sensors in 2040. An Australian quantum sensing industry could create 2,900 new jobs under this scenario and contribute to indirect job creation via flow-on demand and productivity gains.

Civil engineers and geologists can use quantum sensor-based gravity gradiometers to detect buried or hidden structures or cavities many times faster than using ground penetrating radar. By using atomic properties as the reference, quantum sensors can remain accurate indefinitely without costly and/or time consuming recalibration. This reliability can enable high-precision navigation in environments where external reference signals like GPS are too weak or otherwise unreliable. Quantum sensors can also be used to detect structures and changes inside the human body, much like an MRI machine but with a wider range of applications.

Quantum sensors also pose risks to Australia, particularly our military platforms. For example, adversaries could potentially use quantum sensors to more readily and more accurately detect military aircraft and marine vessels. Australia needs to understand the capabilities and limitations of quantum sensors, to enable adjustment of strategies and tactics, or to potentially devise new countermeasures and protections for our armed forces.

Research Impact (RI)

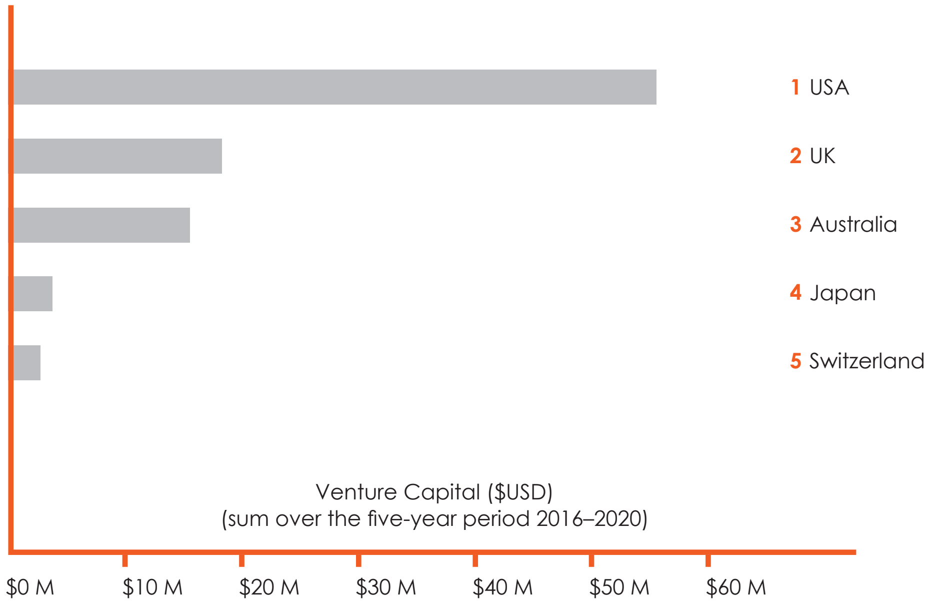
The United States has the highest research impact, with Australia ranked 16th. Total volume of published research has been increasing at around 4% p.a. over the 5 year period 2016–2020, with 39% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

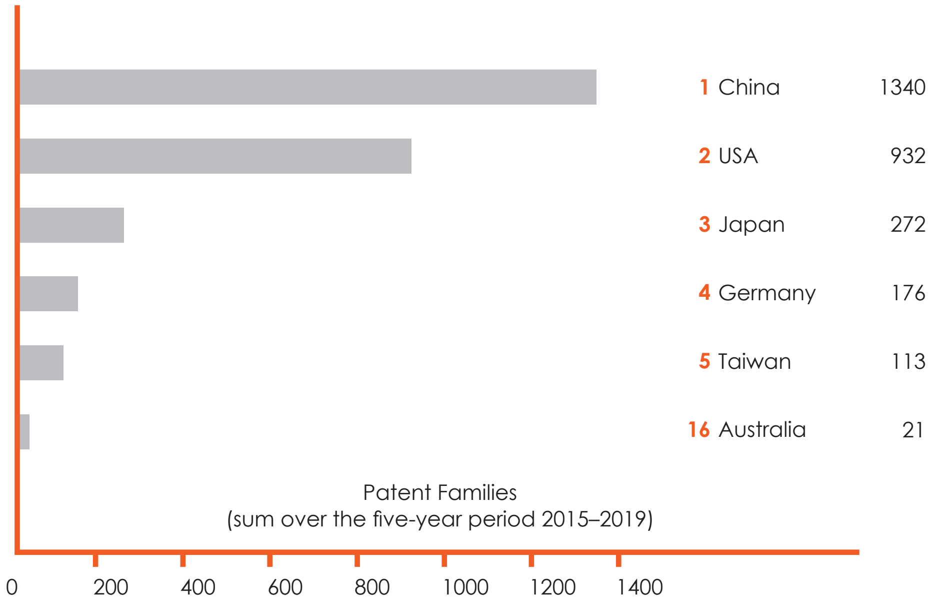
Australia is ranked 3rd for VC investment for quantum sensors, which is led by the United States. Investment in this area has been growing at 50% per annum since 2016.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

The highest number of patents in this technology were filed by applicants or inventors from China, with Australia ranked 16th. Overall, patent applications have been increasing by around 1% p.a. from 2015 to 2019.



Research Institutions – International

The top 2 ranked institutes for research impact are from the United States, and Japan has 3 institutes in the top 10 international institutions.

Rank	Top International Institution	Research Impact
1	Massachusetts Institute of Technology | United States	4178
2	Harvard University | United States	3305
3	National Institute for Materials Science Tsukuba | Japan	2570
4	Chinese Academy of Sciences | China	2382
5	French National Centre for Scientific Research (CNRS) | France	1604
6	Delft University of Technology | Netherlands	1501
7	The University of Tokyo | Japan	1491
8	University of Copenhagen | Denmark	1388
9	RIKEN | Japan	1319
10	National Research Council of Italy | Italy	1250

Research Institutions – Australia

Within Australia, the Australian National University has the highest research impact and is ranked 45th internationally.

Rank	Top Australian Institution	Research Impact
1	Australian National University	490
2	University of Melbourne	312
3	University of Technology Sydney	297
4	Royal Melbourne Institute of Technology University	250
5	University of New South Wales	244
6	Griffith University	217
7	CSIRO	117
8	Macquarie University	111
9	University of Western Australia	103
10	University of Sydney	100

Patents – Australia

Top 5 Australian Patent Applicants	Patent Families
University of Melbourne	4
Royal Melbourne Institute of Technology	2
SIPCO	2
Australian National University	1
CSIRO	1

Patents filed by Australian businesses, 2015–2019.

Inertial navigation systems

Systems and devices that can calculate the position of an object relative to a reference point without using any external references.

Key Sectors

- Agriculture, Forestry and Fishing
- Construction & Manufacturing
- Defence & Defence Industry
- Mining & Resources
- Space
- Transport & Logistics

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security			X

Key Australian Government Actions

Initiatives

- Sovereign Industrial Capability Priorities

Regulations

- Defence and Strategic Goods List 2021

Example Outcomes

- Reduced dependency on GPS and other satellite based navigation systems
- Fast detection and correction of GPS spoofing attacks
- Reliable, high accuracy navigation in dense urban environments
- Faster and more accurate surveying and mapping
- Autonomous systems that can navigate to a specified location even when GPS or other external references (e.g. visible landmarks) are unavailable
- Reliable in-door navigation without site specific infrastructure (e.g. Bluetooth beacons)
- Accurate submarine navigation for long periods without surfacing
- Equitable access for visually impaired people to more shared spaces
- Off-earth and interplanetary satellite and robotics infrastructure

Underpinning Science

ANZ Standard Research Classification

- Applied mathematics
- Software engineering
- Data management and data science
- Electronics, sensors and digital hardware
- Communications engineering
- Computer science
- Electrical engineering
- Optical physics
- Geoinformatics
- Geomatic engineering
- Materials engineering

Example Applications

Readiness Level – Now

- 'Hand-sized', discrete-component high-accuracy fibre optic gyroscopes
- Global Navigation Satellite System (GNSS) augmentation
- Navigation of aircraft, guided weapons, drones, autonomous/underground/underwater vehicles
- Basic motion detectors in mobile phones and robotic systems
- Fitness level tracking
- Movement analysis
- Quantum positioning and compass

Readiness Level – 2–5 years

- Improved dead-reckoning, enabling position estimation with less reliance on GPS systems
- Increased augmentation of dead-reckoning with alternate references; e.g. celestial (star positions), polarised sunlight, 3D reconstruction from imagery
- Wider use cases for autonomous vehicles where GPS may be unavailable; e.g. valleys, underground and underwater
- Enhanced personal and crowd monitoring (physical and mental health) through motion behaviour analysis and improved motion detectors in mobile devices
- Enhanced logistics and supply chain monitoring

Readiness Level – Beyond 5 years

- Miniaturised, embeddable high-accuracy fibre optic gyroscopes
- GPS-quality navigation without access to satellites for longer periods of time (hours) through the use of quantum inertial sensors
- Increased augmentation of dead-reckoning with new sensor and computational capabilities; e.g. magnetic and gravity field mapping, real-time 3D reconstruction from video
- Reliable navigation of autonomous vehicles in urban, forested, valley, underground and underwater environments
- Quantum assisted inertial navigation devices

Australia's place in the world

Australia ranks 8th globally for research impact, led by the University of New South Wales. China has the highest research impact globally for inertial navigation systems (INS), with 8 of the top 10 performing institutions. The United States has more than double the amount of venture capital (VC) investment as the United Kingdom, which rank first and second respectively. Australia is unranked, globally, for VC investment. Global patent activity has been increasing by 15% p.a. since 2015, on average. China leads global patent activity for INS, significantly ahead of the United States; Australia ranks 14th.

Within Australia, Publicly Funded Research Agencies (including universities and CSIRO), small firms and defence industry, are leading work on INS technology. Defence, heavy industry and sea and air transport are driving the existing market for INS; shrinking component sizes and costs are expected to diversify and grow the market for INS, with increased integration of the technology in a broader range of devices and use cases.

Opportunities and Risks

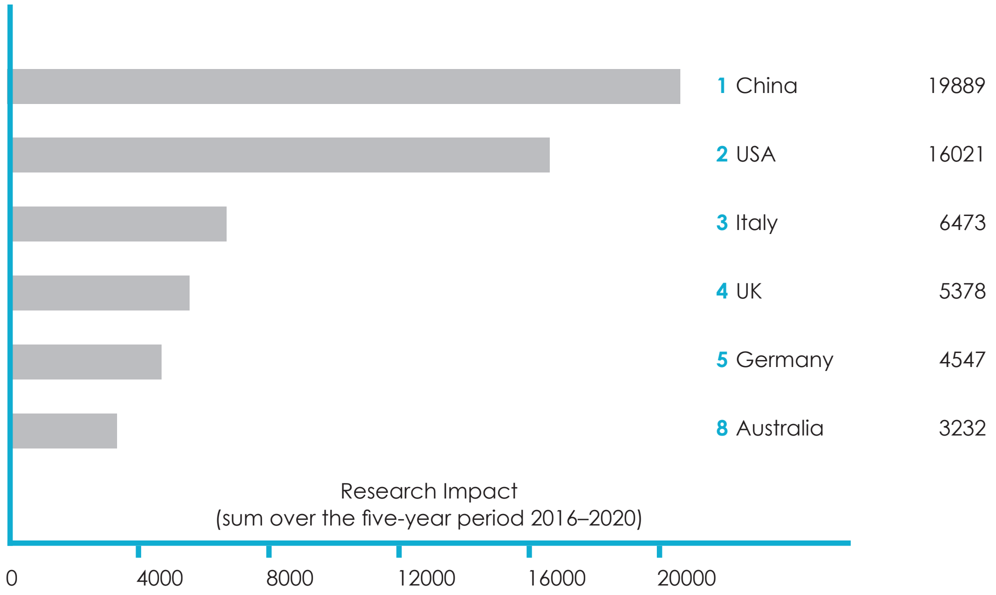
Satellite positioning and navigation has influenced countless aspects of Australia's economy and security in the two decades since high accuracy services first became available to the public. INS promise similar transformational possibilities for environments where satellite positioning and navigation fails to penetrate, such as inside buildings, underground and underwater. Specific opportunities for INS include underground operation of mining vehicles, crewed and un-crewed submarine navigation, autonomous robotic swarms, jamming-resistant guided munitions, increased independence for the visually impaired and improved supply chain and logistics monitoring.

While GPS and similar navigation systems may seem ever-present, there are still many situations and environments where using external references for navigation are impractical, unreliable or impossible; for example, smartphones and other consumer devices generally struggle to receive satellite navigation signals inside large buildings, and even purpose-built professional and military systems stop functioning deep underground or underwater. High accuracy INS can make autonomous systems safer and more reliable by providing a navigational fall-back when external sensory feedback is impaired or fails. For example, INS could detect that an unmanned aerial vehicle (UAV) flying at night is upside-down or that satellite navigation signals may be being spoofed.

Along with the promised benefits of INS, there are considerable risks associated with the potential dual use of such technology. For example, high-accuracy underwater drones offer effective border surveillance, however they can also be used for covert surveillance or malicious intent. Awareness and mitigation of these risks will be required to ensure the benefits are realised, without compromising our security.

Research Impact (RI)

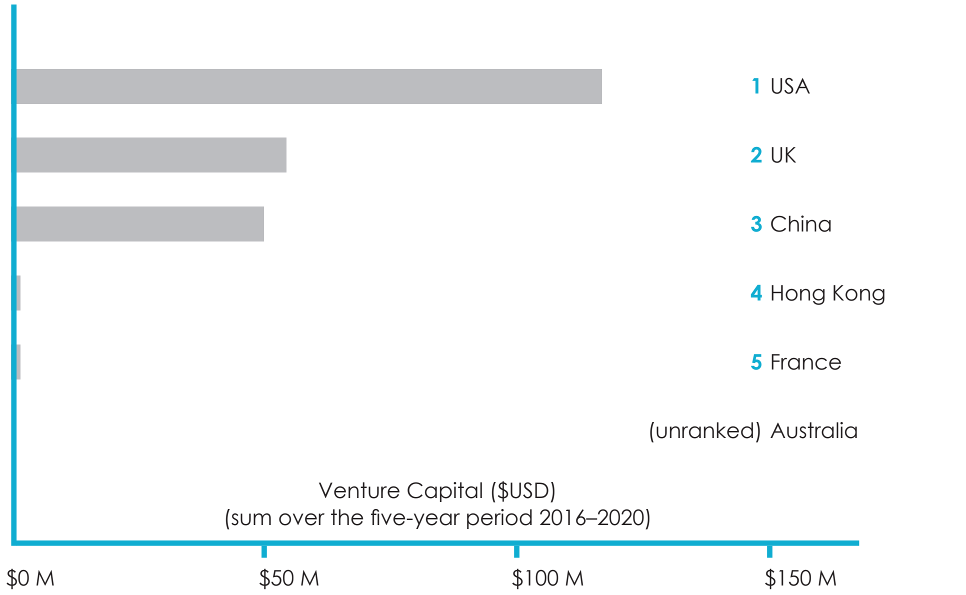
China has the highest research impact in this area, ahead of the United States. Australia is ranked 8th. Total volume of published research has been increasing at 5% p.a. over the five-year period 2016–2020, with 15% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

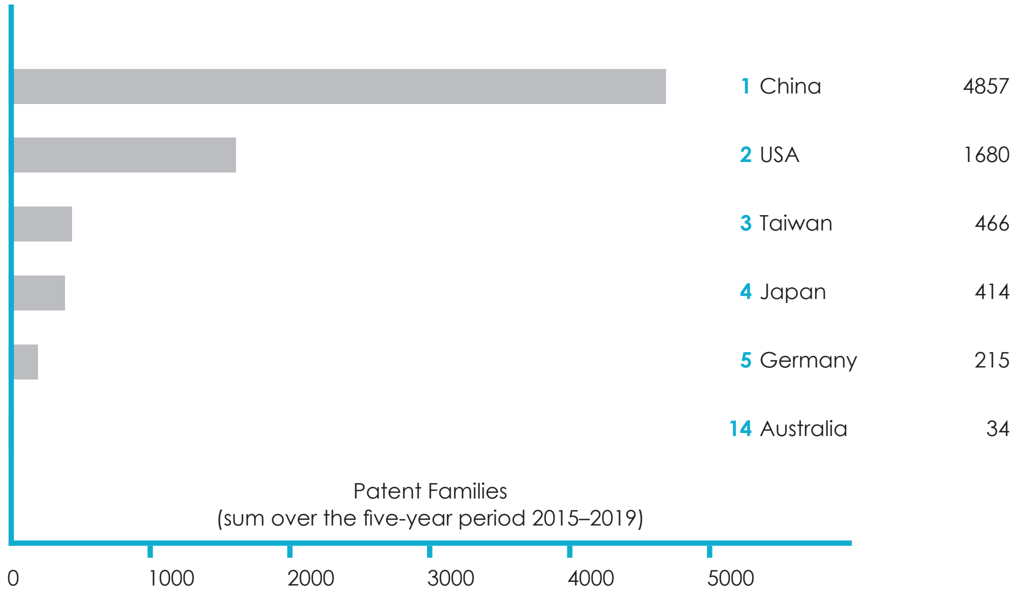
Australia is unranked for VC investment for inertial navigation systems. Investment in this area has been growing at 27% p.a. since 2016. The United States has significantly higher relative amounts of VC investment, well ahead of the United Kingdom.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents - International

The number of patents being lodged annually in this field has been increasing by 15% p.a. since 2015. Most patents in this field were filed by applicants or inventors from China. Australia is ranked 14th.



Research Institutions - International

China has 8 of the top 10 institutions worldwide, including the top 5. Institutions from France and the United Kingdom fill out the top 10.

Rank	Top International Institution	Research Impact
1	Beihang University | China	1966
2	Southeast University, Nanjing | China	1295
3	Chinese Academy of Sciences | China	1222
4	Tsinghua University | China	1134
5	National University of Defense Technology | China	1052
6	French National Centre for Scientific Research (CNRS) | France	917
7	Zhejiang University | China	892
8	Beijing Institute of Technology | China	874
9	Wuhan University | China	817
10	Newcastle University | United Kingdom	807

Research Institutions - Australia

Within Australia, the University of New South Wales has the highest research impact, and is ranked 22nd, internationally. Second ranked, Royal Melbourne Institute of Technology University, is ranked 45th internationally.

Rank	Top Australian Institution	Research Impact
1	University of New South Wales	549
2	Royal Melbourne Institute of Technology University	372
3	University of Melbourne	310
4	University of Queensland	279
5	Queensland University of Technology	266
6	University of Sydney	259
7	CSIRO	256
8	Deakin University	158
9	University of Technology Sydney	146
10	Curtin University	145

Patents - Australia

Top Australian Patent Applicants	Patent Families
CSIRO	4
Underground Extraction Technologies	2
A number of Australian businesses have one patent family recorded in this technology area	

Patents filed by Australian businesses, 2015–2019.

Data current as at 16 March 2022.

Satellite positioning and navigation

Networks of satellites that broadcast precise time signals and other information, which Earth-based devices can use to calculate their location and for navigation. Advanced systems enable greater location accuracy and faster location finding, and greater resistance to unintentional signal interference and intentional jamming or spoofing.

Key Sectors

Impacts all sectors, including:

- Agriculture, Forestry and Fishing
- Banking and Finance
- Communications
- Construction
- Defence and Defence Industry
- Education and Research
- Energy and Environment
- Health
- Manufacturing
- Mining and Resources
- Space
- Transport and Logistics

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security			X

Key Australian Government Actions

Initiatives

- National Infrastructure Positioning Capability (NPIC)
- Southern Position Augmentation Network (SouthPAN) – Australian and New Zealand Satellite Based Augmentation System collaboration
- Ginan: software toolkit and service

Regulations

- National Measurement Act 1960
- National Measurement Regulations 1999

Example Outcomes

- More capable and trustworthy automated resource extraction, enabling a more competitive resource sector
- More reliable automated vehicles, able to determine their location accurately even in traditionally hard-to-reach environments
- A safer defence force, with navigation devices which are resistant to location jamming or spoofing
- Greater convenience for consumers, with devices determining their location more quickly and accurately
- More reliable and efficient transport and logistics networks that are better able to transmit location details
- More accurate tracking of automated capital equipment to prevent damage
- Accurate automated land and animal management. including weed and pest management, cropping and water management and animal welfare solutions
- Better knowledge of the precise locations of space and ground assets

Underpinning Science

ANZ Standard Research Classification

- Aerospace engineering
- Aerospace transport
- Applied mathematics
- Astronomical sciences
- Computer science
- Human-computer interaction
- Cybersecurity
- Data privacy
- Pulsar astronomy
- Software engineering
- Data management and data science
- Electronics, sensors and digital hardware
- Communications engineering
- Electrical engineering
- Optical physics
- Geoinformatics
- Geomatic engineering

Example Applications

Readiness Level – Now

- Navigation tools for transport and logistics, including optimal routing and asset tracking
- Positioning, navigation and timing (PNT) certification in financial transactions
- Spatiotemporal analytics, for example to understand wildlife migration patterns and predict future positions
- Surveying and mapping
- Animal welfare management in agricultural settings
- Automated weed and pest and land use decision making
- Livestock and wildlife tracking via location markers in or on animals
- Secure PNT using pulsar signals on Earth and beyond

Readiness Level – 2–5 years

- Enhanced digital identity management using location information
- More resilient and available information services due to convergent timing, communication and sensing satellite systems
- Broader access to PNT in remote and challenged environments (mountainous terrain, indoors, etc.) through novel satellite signal processing
- Hybrid PNT using satellites, pulsar astronomy and quantum technology in challenged environments
- Improves safety and road management using vehicle location data

Readiness Level – Beyond 5 years

- Fast, secure financial transactions (digital money with PNT anti-fraud authentications)
- Digital twin of the entire globe as a virtual world (including scenario modelling)
- Off earth position and navigation infrastructure in moon, Mars and beyond
- Coordinated space time coordinates for Australian satellites

Opportunities and Risks

Advancements in satellite positioning and navigation systems promise to increase the accuracy of spatiotemporal data for use in predictive models, and for autonomous systems, it also underpins precision timing that is required across all sectors of the economy. It further allows machines that require highly precise and accurate location information to do more work, including optimising resource extraction. Precise location signals can enable financial institutions to improve fraud detection services. Increased accuracy in positioning and navigation will create greater efficiencies, including time and fuel consumption for logistics and transport. This technology opens up numerous opportunities in the agriculture and environment sectors as well, for example, improved agricultural and natural environment performance by removing the 'human decision making' component of agricultural production by automating land management.

Many current technologies, supply chain logistics, businesses and critical infrastructure rely heavily on the existing satellite position, navigation and timing (PNT) infrastructure, which may make them vulnerable if this infrastructure is disrupted or destroyed. The loss of this capability could cause physical and economic damage and undermine Australia's national security. PNT satellites form constellations in Medium Earth Orbit (MEO) and there is intense competition and a lack of shared responsibility for the management and preservation of this part of the space domain, resulting in increased congestion. Satellite infrastructure is also vulnerable to other physical risks, such as solar storms and high-altitude electro-magnetic pulse devices. Satellites are also not impervious to cyber-attacks, and so various threats must be mitigated, including denial-of-service attacks, and spoofing of various kinds.

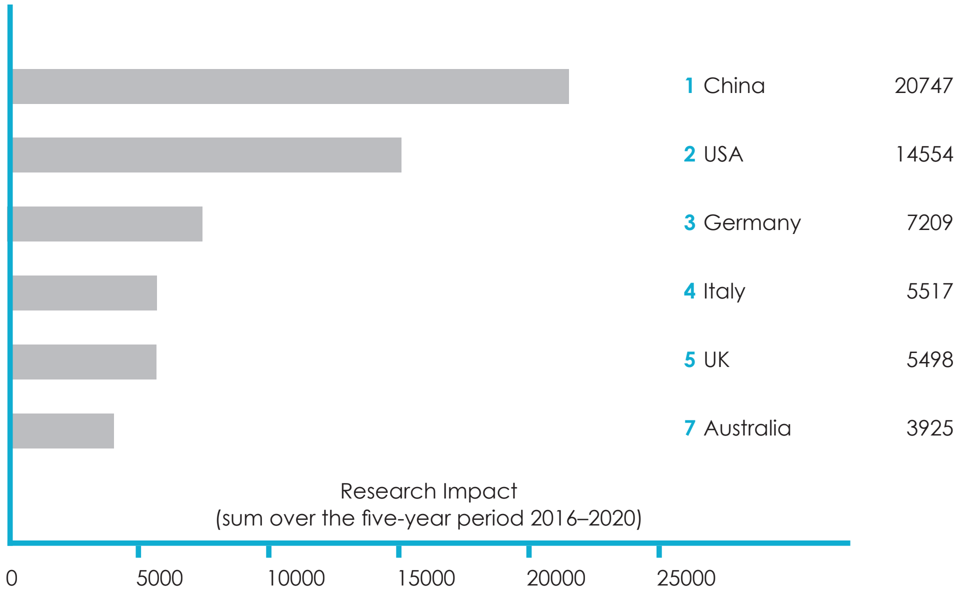
Australia's place in the world

Australia ranks 7th for research impact, led by the University of New South Wales, which ranks 13th internationally. Internationally, China has the highest research impact, followed by the United States. China has 5 of the top 10 research institutions and the United States, France and Germany constitute the remainder of the top 10. Venture capital is led by the United States followed by China, and has been growing at 40% p.a. since 2016. Globally, new patents lodged have been increasing by 10% since 2016. China has the most, followed distantly by the United States. Australia ranks 12th in patents lodged, and is unranked for venture capital.

Satellite positioning and navigation are an important part of Australia's commercial activities, including our reliance on PNT in agriculture infrastructure enabling crop harvest with minimal human intervention. We conduct world-leading research in this field, and our various commercial and defence interests are supported by international partners providing us access to their existing PNT satellite networks.

Research Impact (RI)

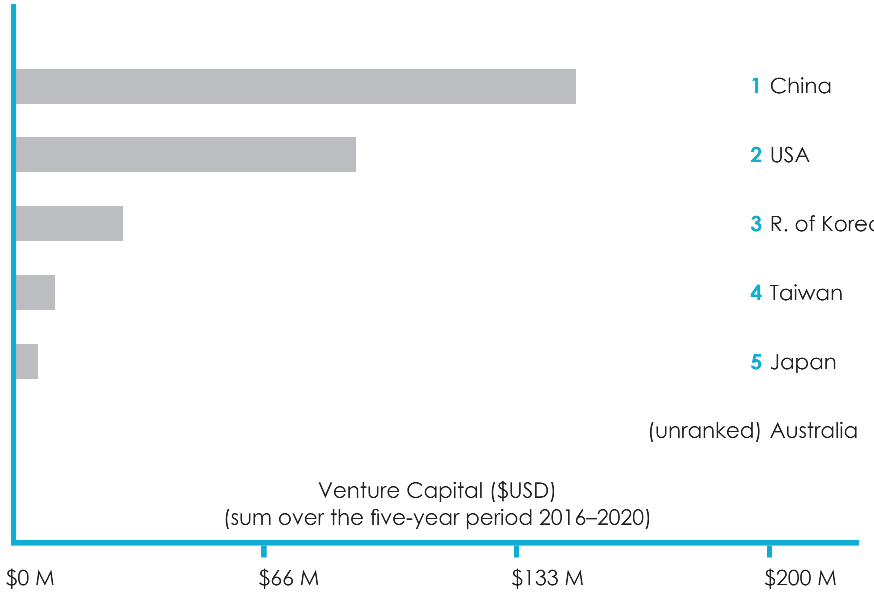
China has the highest research impact in this area, ahead of the United States. Australia is ranked 7th. Total volume of published research has been increasing at 8% p.a. over the 5 year period 2016–2020, with 20% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

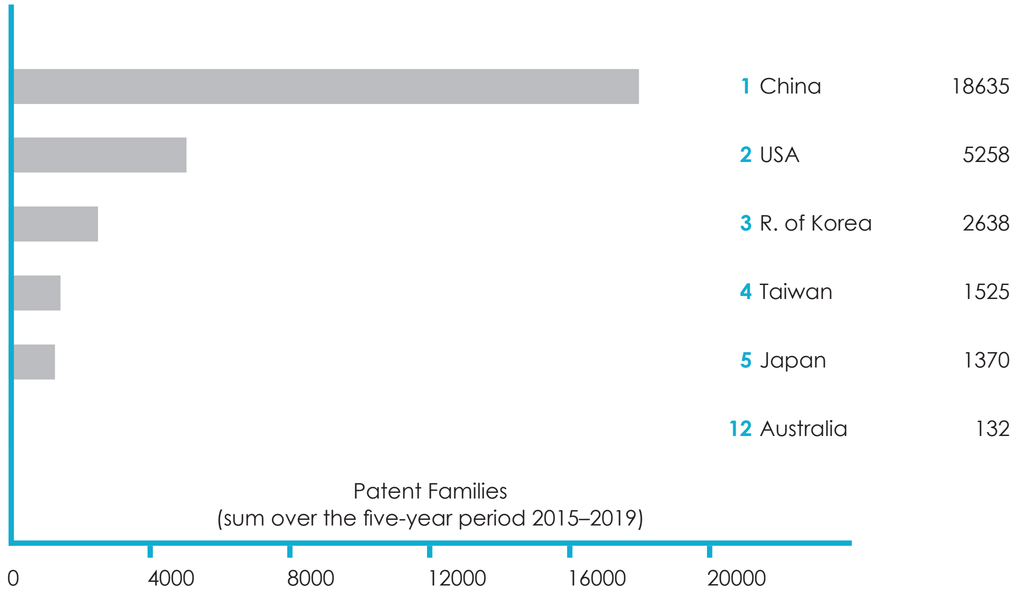
Australia is unranked for VC investment in this area. Investment has been growing at 40% p.a. since 2016. The United States has the highest amount of VC investment, ahead of China.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents - International

The number of patents being lodged annually in this field has been increasing by 10% p.a. since 2015. Most patents in this field were filed by applicants or inventors from China, over 3 times more than the United States. Australia is ranked 12th.



Research Institutions - International

China has 5 of the global top 10 institutions, including the top 3. Germany, France and the United States make up the remaining institutions in the top 10.

Rank	Top International Institution	Research Impact
1	Wuhan University | China	4547
2	Chinese Academy of Sciences | China	3316
3	Beihang University | China	2199
4	Helmholtz Centre Potsdam - German Research Centre for Geosciences | Germany	2190
5	German Aerospace Center | Germany	1957
6	Tsinghua University | China	1937
7	University of Chinese Academy of Sciences | China	1743
8	French National Centre for Scientific Research (CNRS) | France	1480
9	California Institute of Technology | United States	1320
10	Jet Propulsion Laboratory, California Institute of Technology | United States	1302

Research Institutions - Australia

Within Australia, the University of New South Wales has the highest research impact. Three Australian institutions are ranked in the international top 50 – University of New South Wales 13th, Curtin University 23rd, and Royal Melbourne Institute of Technology University 43rd.

Rank	Top Australian Institution	Research Impact
1	University of New South Wales	1051
2	Curtin University	683
3	Royal Melbourne Institute of Technology University	550
4	Queensland University of Technology	290
5	University of Technology Sydney	257
6	University of Melbourne	192
7	University of Sydney	188
8	University of Tasmania	132
9	Monash University	123
10	CSIRO	72

Patents - Australia

Top Australian Patent Applicants	Patent Families
Myriota	4
Defendtex	2
Propeller Aerobotics	2
Spatial Information Systems Research	2
A number of Australian businesses have one patent family recorded in this technology area	

Patents filed by Australian businesses, 2015–2019.

Data current as at 16 March 2022.

Advanced robotics

Robots capable of performing complex manual tasks usually performed by humans, including teaming with humans and/or self-assembling to adapt to new or changed environments. Applications for advanced robotics include industry and manufacturing, defence and public safety, and healthcare and household tasks.

Key Sectors

- Agriculture
- Health
- Communications
- Defence & Defence Industry
- Energy & Environment
- Transport & Logistics
- Space
- Mining & resources

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security			X

Key Australian Government Actions

Initiatives

- Modern Manufacturing Strategy
- Next Generation Technologies Fund
- CRC for Trusted Autonomous Systems
- Australia's Critical Minerals Strategy promoting innovation in the sector
- Digital Economy Strategy – Artificial Intelligence Centre to drive adoption of AI technologies in business
- Advancing Space: Australian Civil Space Strategy 2019-2028
- Artificial Intelligence Action Plan
- National Collaborative Research Infrastructure Strategy
- CSIRO Robotics and Autonomous Systems Group
- 2020 Force Structure Plan

Regulations

- Defence and Strategic Goods List 2021
- Work Health and Safety Regulations 2011

Example Outcomes

- Improved farm productivity through better efficiency and precision
- Increased labour efficiency across all sectors
- Improved animal welfare outcomes
- Improved environmental outcomes through enhanced monitoring
- Improved health outcomes from surgical and diagnostic robots and systems
- Improved health outcomes for patients in remote areas, where robots can complement human healthcare professionals
- Greater care capacity of trained staff with the addition of assistance robots in health and aged care
- Improved throughput, safety and accuracy from automated mining and port operations
- Improved supply chain security through local robotic manufacturing of critical components
- Expanded defence capabilities and operations
- Enhanced ability to respond to disasters, for example bushfires and search and rescue operations

Underpinning Science

ANZ Standard Research Classification Category

- Control engineering, mechatronics and robotics
- Electrical engineering
- Electronics, sensors and digital hardware
- Artificial intelligence
- Computer vision and multimedia computation
- Human-centred computing
- Information systems
- Machine learning
- Software engineering

Example Applications

Readiness Level – Now

- Industrial robots (welding, spraying, cutting, material handling, machine tending)
- Robots for manufacturing, stevedoring, mining, including cobots
- Logistics robots (automated guided vehicles, pick and pack robots)
- Exoskeleton, robotic mule, robotic limbs
- Surgical robots (minimally invasive surgery)
- Care and hospital robots
- Robotic farm systems for cropping and irrigation
- Robots for emergency applications: search and rescue, firefighting
- Robots for security applications: threat detection, bomb disposal

Readiness Level – 2–5 years

- Deployable and adaptive communication networks
- Air traffic management/safety e.g. counter uninhabited air systems
- Emergency response and firefighting, including swarms for rapid search and rescue

Readiness Level – Beyond 5 years

- Health and aged care service robots
- Ingestible (robot) therapies (nanobots)
- Robotic telemedicine and surgery
- 3D printing robots for macro-structures (novel architecture, space applications and extra-terrestrial habitats)
- Novel security and surveillance, including expansion in space, aero and undersea (including potential convergence with quantum technologies)
- Convergence of robots with machine learning and artificial learning

Australia's place in the world

The United States has the highest research impact in this field, significantly ahead of 2nd ranked Italy, which specialises in high tech robots such as surgical and medical robotics.
Australia ranks 9th and China fourth in research impact in this field. The University of New South Wales has the highest research impact for Australian institutions for advanced robotics, ahead of the University of Sydney and Queensland University of Technology. The United States has significantly higher amounts of venture capital (VC) investment compared to China, while China has the most patents.

While the manufacturing sector has traditionally led the way in deploying robotic technologies, the Australian mining sector is now world leading in robotic technologies to improve exploration, logistics and safety, increase productivity and efficiency and reduce operating costs. Beyond the mining sector, these advancements will have flow on applications across many sectors, such as space exploration, agricultural processes, and access for environmental applications.

Opportunities and Risks

Australian productivity and way of life will be significantly affected by advanced robotics. There are already examples of robotics being used in traditional labour intensive roles, such as brick laying , fruit picking, weed control and warehouse packing. As robotic technologies, and other convergent fields advance, robotics will have a place in the skilled workforce, for example in surgery which has been shown to contribute to improved outcomes by less invasive procedures and standardised surgical approaches.

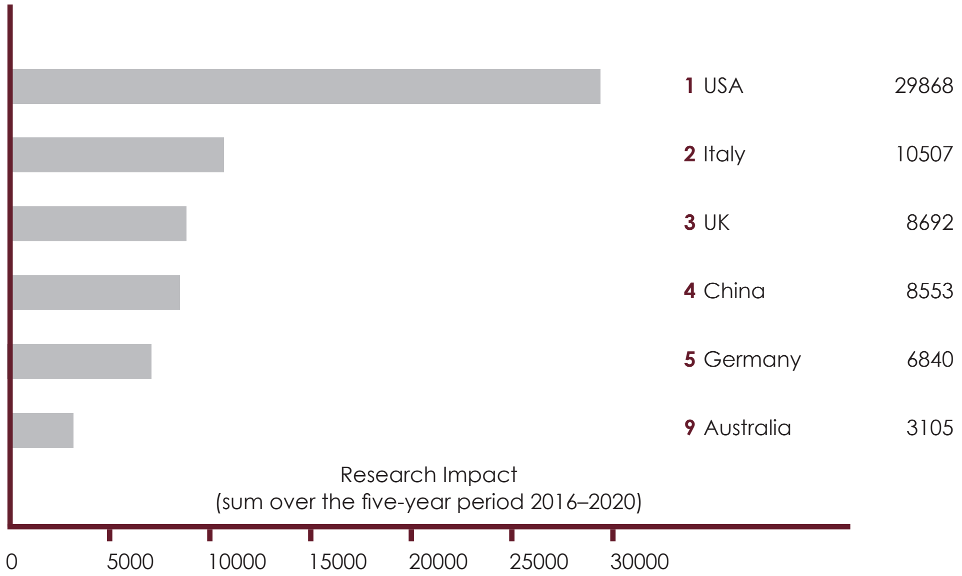
The immense improvements in productivity from increased automation and robotics will enable Australia to compete globally and build a resilient manufacturing sector, and maintain our world leading mining capabilities. Increased productivity and automation will create new and different jobs for people across all sectors.

Robotics design is generally optimised for functionality which may not consider security during development. This approach creates a high chance of deployment of robotic technology with significant vulnerabilities to cyber-attack both directly to the robotic device and to the associated infrastructure such as data storage, learning models and so on. As robotics and autonomous systems advance and converge, there is a risk that this capability will be subject to both intentional and unintentional interference resulting in undesirable outcomes to individuals or systems. This risk is potentially further compounded by an over-assumption of the capability of the robotic system. These risks need to be carefully considered and mitigated to ensure the full potential of robotic technologies is realised, without compromise of human safety and security.

The successful deployment and realisation of advanced robotics is also dependent on reliable supporting infrastructure, such as high speed wireless communications, and a skilled workforce to build, operate and maintain these systems

Research Impact (RI)

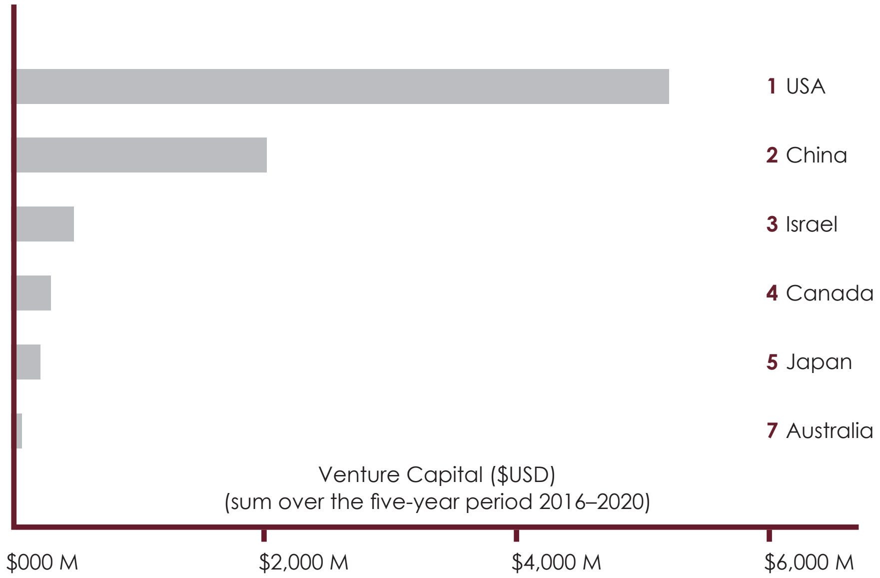
Australia ranks 9th for research impact in a field where the United States has the highest research impact ahead of Italy (2nd) and the United Kingdom and China. Total volume of published research has increased at around 12% p.a., over the 5 year period 2016–2020, with 19% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

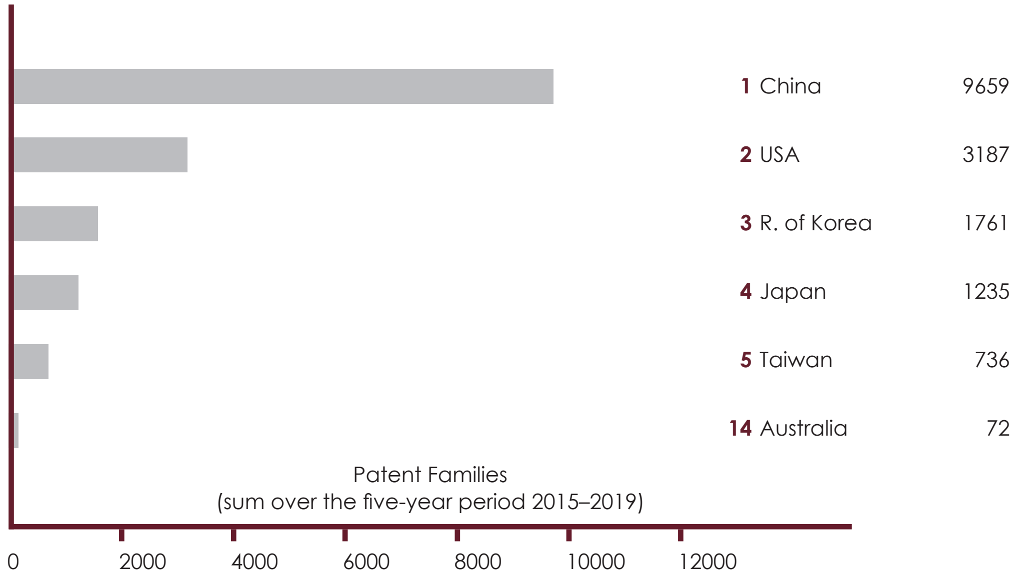
The United States has the greatest amount of venture capital (VC) investment in this area with more than 3 times the amount that's invested in China; Australia has the 7th highest level of investment. Investment globally in this area has been growing at 22% p.a. since 2016.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

Most patents for this technology were filed by Chinese applicants or inventors, with 3 times the number of the United States. Australia ranks 14th. Overall patent applications have been increasing at 15% annually since 2015.



Research Institutions – International

The United States has 5 institutions in the top 10 international institutions. The remainder of the top 10 international research institutions includes institutions from Europe and the United Kingdom.

Rank	Top International Institution	Research Impact
1	Harvard University | United States	2611
2	Stanford University | United States	2407
3	Johns Hopkins University | United States	1672
4	French National Centre for Scientific Research (CNRS) | France	1471
5	Massachusetts Institute of Technology | United States	1367
6	Sant'Anna School of Advanced Studies | Italy	1362
7	Imperial College London | United Kingdom	1333
8	Cornell University | United States	1278
9	University College London | United Kingdom	1257
10	University of Naples Federico II | Italy	1093

Research Institutions – Australia

Within Australia, the University of New South Wales has the highest research impact. All Australian institutions are currently outside the international top 50.

Rank	Top Australian Institution	Research Impact
1	University of New South Wales	454
2	University of Queensland	305
3	Queensland University of Technology	295
4	Monash University	276
5	University of Sydney	264
6	University of Wollongong	222
7	University of Technology Sydney	201
8	University of Melbourne	188
9	Deakin University	178
10	Peter Maccallum Cancer Centre	68

Patents – Australia

Top 5 Australian Patent Applicants	Patent Families
Fastbrick Intellectual Property	8
Automation Innovation	2
Leica Biosystems Melbourne	2
Simplify Medical	2
CSIRO	1

Patents filed by Australian businesses, 2015–2019.

Autonomous systems operation technology

Self-governing machines that can independently perform tasks under limited direction or guidance by a human operator. Applications include passenger and freight transport, un-crewed underwater vehicles, industrial robots, public safety and defence.

Key Sectors

Influences all sectors of the economy, including:

- Agriculture
- Banking & Finance
- Communications
- Construction
- Defence & Defence Industry
- Energy & Environment
- Health
- Transport & Logistics
- Education & Research
- Mining & Resources
- Manufacturing
- Space

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security			X

Key Australian Government Actions

Initiatives

- Digital Economy Strategy including National Emerging Aviation Technologies Policy Statement and Partnerships
- Office of Future Transport Technology – National Policy Framework for Land Transport Technology and Action Plan
- 2020 Force Structure Plan
- Next Generation Technologies Fund
- CRC for Trusted Autonomous Systems
- Positioning Australia Program
- Advancing Space: Australian Civil Space Strategy 2019-2028
- Artificial Intelligence Action Plan
- CSIRO Robotics and Autonomous Systems Group
- Modern Manufacturing Strategy
- National Collaborative Research Infrastructure Strategy

Regulations

- Civil Aviation Act 1988
- Civil Aviation Safety Regulations 1988
- National Drone Detection Network
- Defence and Strategic Goods List 2021

Example Outcomes

- Improved logistics and traffic management
- Increased mine productivity and safety from autonomous systems used for detection, extraction and transport
- Increased efficiency in agriculture through the use of autonomous systems for labour intensive or riskier tasks, e.g. weed management, crop spraying, picking
- Improved environmental outcomes through enhanced monitoring and responses, including management of feral pests
- Enhanced and expanded defence capabilities and operations
- Increased capacity to monitor and respond to public safety needs, such as for bushfires and search and rescue operations
- Expanded space operations through improved accuracy of operations and increased access to extra-terrestrial environments
- Better patient outcomes from surgical robotics
- Buildings constructed entirely by robots

Underpinning Science

ANZ Standard Research Classification Category

- Control engineering, mechatronics and robotics
- Electrical engineering
- Electronics, sensors and digital hardware
- Artificial intelligence
- Computer vision and multimedia computation
- Human-centred computing
- Information systems
- Machine learning
- Software engineering
- Aerospace engineering
- Communications engineering
- Computer vision
- Image processing
- Photogrammetry and remote Sensing
- Geospatial information systems and geospatial data modelling
- Navigation and position fixing
- Surveying
- Networking and communications
- System and network security

Example Applications

Readiness Level – Now

- Spot weeding and herding stock in agriculture
- Autonomous transport in defined locations: shuttle buses on campus, trains transporting passengers between airport terminals, mining operations improving efficiency and safety with autonomous haulage systems
- Security monitoring by self-deploying and self-charging drones
- Warehouse operations with minimal human involvement
- Lunar and Martian rovers
- Auto-deploying speed bumps and/or bollards

Readiness Level – 2–5 years

- Autonomous searches for survivors in collapsed buildings and natural disasters
- Autonomous transport systems for shipping containers
- Autonomous military applications: drones, flying ambulance shuttles on the battlefield, optional crewed vehicles, electronic warfare, logistic resupply, battle buddies, surveillance, cognitive radios and communication
- High altitude, solar-powered aerial drones performing pseudo-satellite functions (only occasionally returning to earth for servicing)

Readiness Level – Beyond 5 years

- Full integration of autonomous transport (cars, buses, trucks, trains) into urban, highway and rural traffic
- Modular, self-healing autonomous building 'blocks' that can assemble into any infrastructure asset needed: mobile bridges, runways, take-off pads, road segments, shelters
- Modular, self-healing satellite systems
- Robotic assistants
- Autonomous rescue

Australia's place in the world

The United States has the highest research impact in this area and also has 6 institutions in the top 10 internationally, including each of the top 3. China is 2nd. Australia is ranked 7th internationally for research impact, and the highest ranked University of New South Wales, is ranked 22nd internationally. Eight of the top 10 research institutes are from Five Eyes nations. The United States has the highest venture capital (VC) investment ahead of China and Japan; Australia is unranked. Globally, the number of patents has been increasing at around 22% p.a. since 2015, with the United States having the greatest number of patents, approximately 3 times the amount of 2nd ranked Japan which has slightly more patents than China; Australia is ranked 17th.

The United States is the global leader in autonomous systems operation technology, with significantly higher research impact, VC investment and patent filings than second ranked China.

Opportunities and Risks

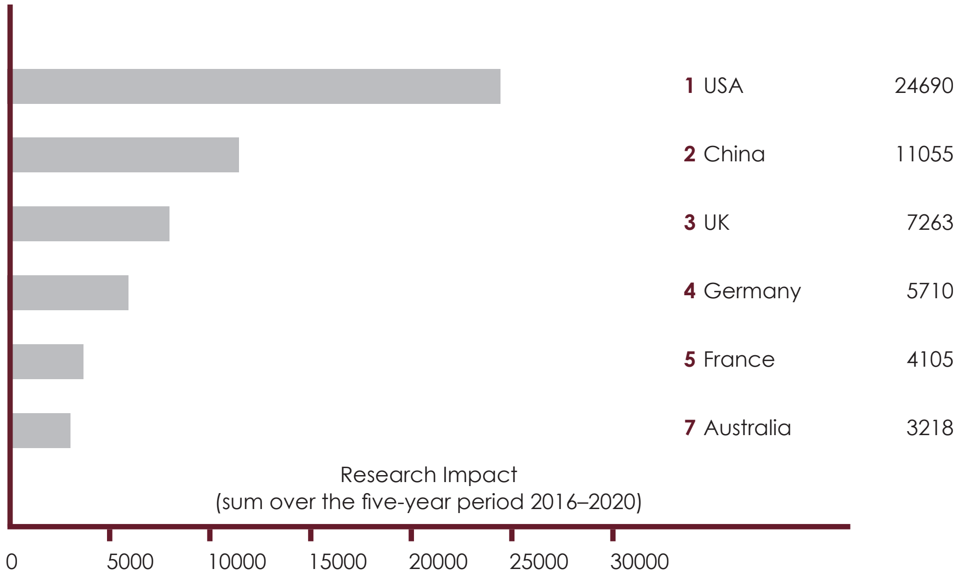
Autonomous systems operation technology promises to make Australia safer and more productive. These systems can replace humans in dangerous environments, such as underground mine sites, or when dealing with hazardous chemicals. Autonomous systems can also protect people and the environment, by enabling continuous or more frequent monitoring of places like national parks, unpatrolled beaches and sensitive heritage sights. Autonomous systems can make living outside Australia's major urban centres more cost effective by reducing transport cost and making services more frequent. Autonomous systems can also enable older Australians to retain their independence, by reducing the cost of providing 24/7 support at home and in the community.

Autonomous systems operation technology is not without risk to Australia. Depending on the systems under their control, flawed or compromised autonomous systems could damage property and cause injury or even death. Autonomous systems will almost certainly replace some jobs, while also creating new ones. In the absence of sufficient oversight and regulation, autonomous systems may be used in ways that infringe upon individual Australians' privacy and autonomy. Autonomous systems operation technology, by reducing or eliminating direct human involvement, may also embolden geostrategic rivals, particularly between nations with differing access to the technology.

The development of standards for autonomous systems generally lags behind technological innovation and diffusion into applications, creating regulatory risks. There may also be differences in the value of these systems internationally, resulting in some states introducing, and potentially exporting, systems and applications that others would prohibit.

Research Impact (RI)

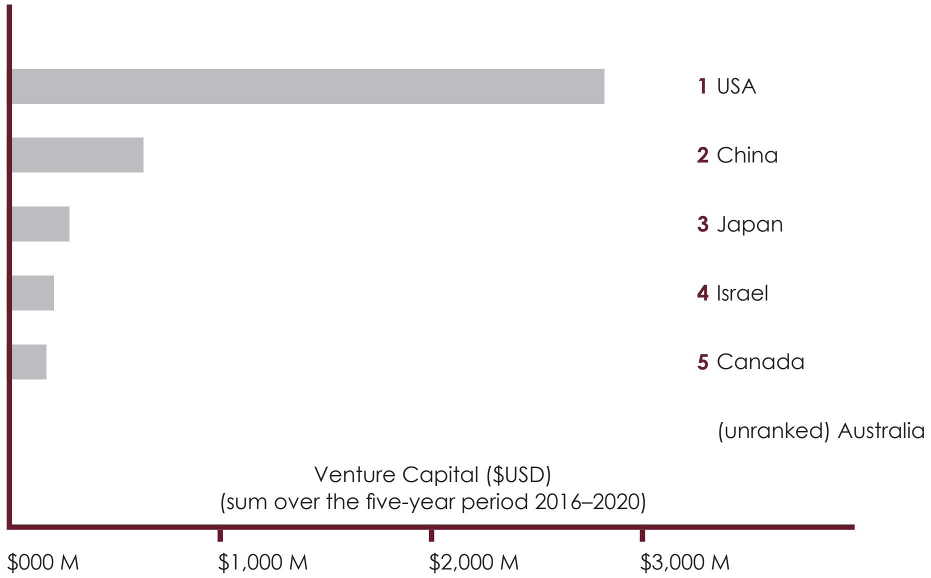
The United States has the highest research impact in this area, ahead of China, with Australia ranked 7th. Total volume of published research has been increasing at 29% p.a. over the 5 year period 2016–2020, with 19% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

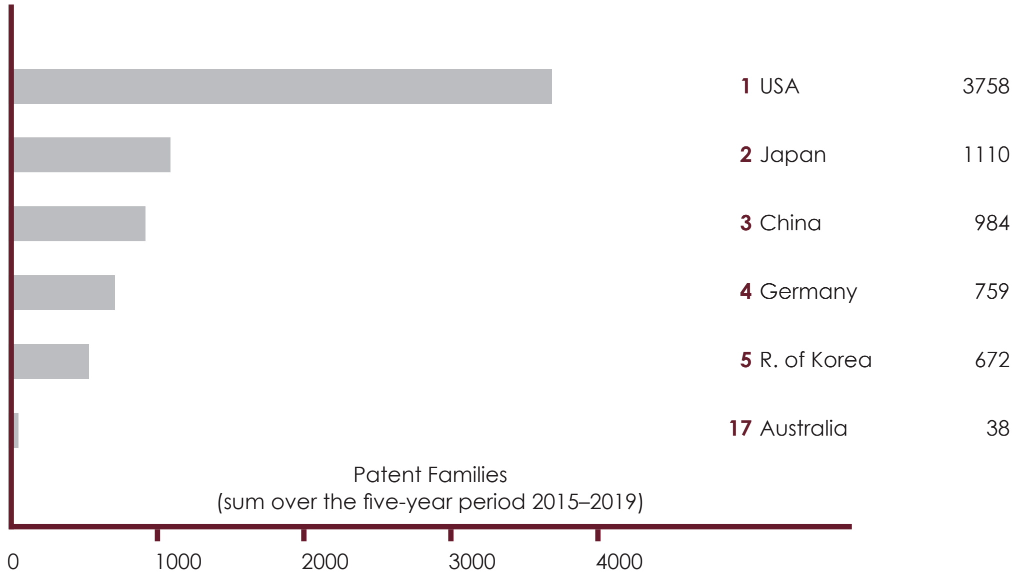
The USA has significantly higher amounts of venture capital (VC) investment, well ahead of China and Japan. Australia is unranked for VC investment in autonomous systems technology. Investment in this area has been growing at 34% per annum since 2016.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

The highest number of patents for this technology were filed by applicants or inventors from the United States, ahead of Japan and China. Australia ranks 17th. Overall patent applications have been rising by 22% since 2015.



Research Institutions – International

The United States has 6 institutes in the top 10 international institutions, including each of the top 3 institutions. China, Canada, France and the United Kingdom make up the remaining institutes.

Rank	Top International Institution	Research Impact
1	Massachusetts Institute of Technology | United States	2418
2	Stanford University | United States	1938
3	University of Texas at Austin | United States	1625
4	Tsinghua University | China	1599
5	French National Centre for Scientific Research (CNRS) | France	1522
6	University of California at Berkeley | United States	1503
7	University of Waterloo | Canada	1355
8	University of Oxford | United Kingdom	1275
9	Carnegie Mellon University | United States	1213
10	University of Michigan, Ann Arbor | United States	1045

Research Institutions – Australia

Within Australia, the University of New South Wales has the highest research impact and is ranked 22nd internationally.

Rank	Top Australian Institution	Research Impact
1	University of New South Wales	672
2	University of Melbourne	366
3	Royal Melbourne Institute of Technology University	349
4	University of Sydney	336
5	Queensland University of Technology	252
6	Monash University	235
7	Deakin University	205
8	University of Technology Sydney	169
9	CSIRO	103
10	Australian National University	75

Patents – Australia

Eight Australian businesses filed one patent each for this technology from 2015 to 2019.

Drones, swarming and collaborative robotics

Uncrewed air, ground, surface and underwater vehicles and robots that can achieve goals with limited or no human direction, or collaborate to achieve common goals in a self-organising swarm. Applications for drones, swarming and collaborative robots include public safety, environmental monitoring, agriculture, logistics, and defence.

Key Sectors

- Agriculture
- Health
- Communications
- Defence & Defence Industry
- Energy & Environment
- Transport & Logistics
- Space

Estimated impact on national interest	Low	Med	High
Economic Prosperity			X
National Security			X

Key Australian Government Actions

Initiatives

- Digital Economy Strategy including National Emerging Aviation Technologies Policy Statement and Partnerships
- Office of Future Transport Technology – National Policy Framework for Land Transport Technology and Action Plan
- 2020 Force Structure Plan
- Next Generation Technologies Fund
- CRC for Trusted Autonomous Systems
- Positioning Australia Program
- Advancing Space: Australian Civil Space Strategy 2019–2028
- Artificial Intelligence Action Plan
- CSIRO Robotics and Autonomous Systems Group
- Modern Manufacturing Strategy
- National Collaborative Research Infrastructure Strategy

Regulations

- Civil Aviation Act 1988
- Civil Aviation Safety Regulations 1988
- National Drone Detection Network
- Defence and Strategic Goods List 2021

Example Outcomes

- Increased farm productivity, reduced reliance on chemical usage, and reduced wastage
- Increased labour efficiency in the agriculture sector
- Management of livestock and feral animals
- Improved environmental outcomes through enhanced monitoring and responses
- New avenues for the arts, journalism and entertainment, such as aerial and remote access photography and videography, and light shows
- Enhanced and expanded defence capabilities and operations
- Enhanced and expanded border surveillance
- More detailed and more frequently updated digital maps
- Increased capacity to monitor and respond to public safety needs, such as for bushfires and search and rescue operations
- Greater capacity for aerial deliveries and improved logistics and traffic management

Underpinning Science

ANZ Standard Research Classification Category

- Control engineering, mechatronics and robotics
- Electrical engineering
- Electronics, sensors and digital hardware
- Artificial intelligence
- Computer vision and multimedia computation
- Human-centred computing
- Information systems
- Machine learning
- Software engineering
- Aerospace engineering
- Communications engineering
- Computer vision
- Image processing
- Photogrammetry and remote Sensing
- Geospatial information systems and geospatial data modelling
- Navigation and position fixing
- Surveying
- Networking and communications
- System and network security

Example Applications

Readiness Level – Now

- Recreational drones for nature photography, sports videography and drone swarm light show (entertainment)
- Surveys and mapping
- Farm monitoring for optimal cropping, weed spraying and irrigation
- Wildlife monitoring such as beach shark patrol, biodiversity and habitat monitoring
- Reforestation with tree-planting drones
- Urgent deliveries (e.g. blood and medicine)
- Weather forecasting and modification
- Collaborative systems for security applications and police work
- Solar-powered high-altitude pseudo satellite drones for surveillance and communication

Readiness Level – 2–5 years

- Health and aged care service robots
- Last mile drone delivery of goods for transport and logistics
- Air traffic management/safety
- Driverless combined transport (e.g. buses and cars)
- Emergency response and firefighting, including swarms for rapid search and rescue
- Semi-autonomous and autonomous systems for defence

Readiness Level – Beyond 5 years

- City-wide drone swarm for rapid delivery of defibrillators and other lifesaving items
- Underwater sensor network for water quality monitoring
- Deployable and adaptive communication networks
- Security and surveillance, including expansion in space, aero and undersea
- Collaborative robotic swarms to move heavy items
- Chemical, biological, radiation, nuclear locating and tracking swarm (convergence with autonomy)
- Unmanned military air systems including airborne early warning and control, air-to-air refuelling, anti-submarine warfare

Australia's place in the world

Australia ranks 9th for research impact, led by the University of New South Wales, which ranks 11th internationally. China has the highest research impact and has 6 institutions in the top 10 international institutions. Venture capital investment is led by the United States and China, with Israel having the 3rd highest VC investment. Globally, the number of patents has been increasing at around 3% p.a., with the United States having the greatest number of patents, with Australia in 13th.

Australia's strengths in foundational and applied research in this area cut across many sectors, including agriculture, advanced manufacturing, mining, and biodiversity and biosecurity. The CSIRO has been at the forefront of the development and real-world operation of long-range fully autonomous Unmanned Aerial Systems, which has focused on remote sensing in remote locations and inhospitable terrain. The University of New South Wales Defence Research Institute has key expertise in trusted AI enabled shepherding of human-swarm teams for defence and civilian applications.

Opportunities and Risks

These autonomous systems will significantly affect Australian productivity and way of life. There is considerable potential for increased productivity in existing sectors and opening up new industrial sectors will result in improved economic sovereignty for Australia and jobs growth. In the logistics sector there are opportunities to improve safety.

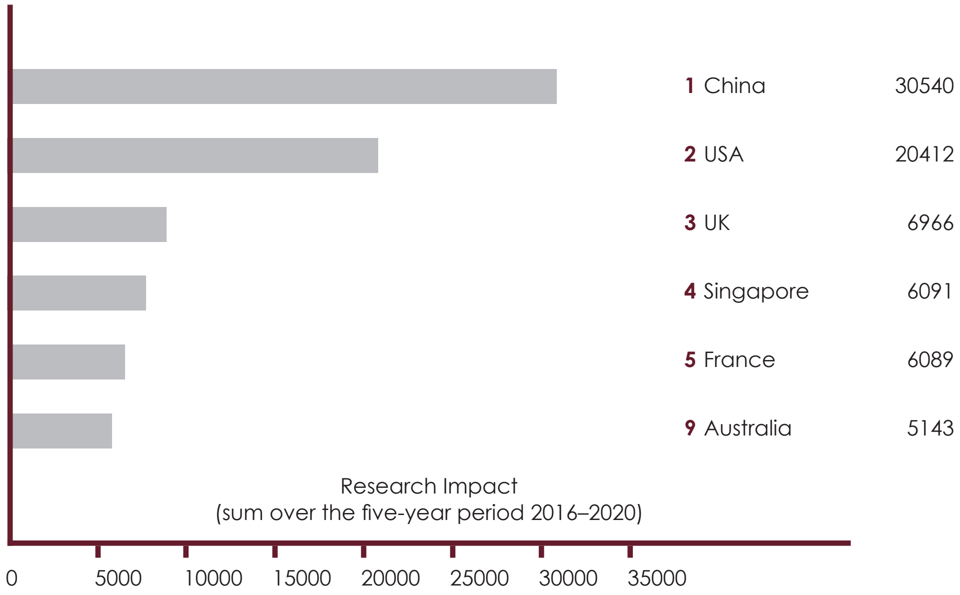
Drones, swarming and collaborative robots rely on an interconnected system of technologies, including AI and machine learning. As such these technologies are subject to cyber risks and vulnerabilities, not just to the final system of technologies working together, but also the individual component. There are also vulnerabilities associated with the interactions of the components of the system. This risk is further compounded by a lack of assured supply chain for key technologies in this area. Australia is building partnerships with key allies in this area to leverage our research capability and create a trusted supply chain.

Drone swarms have the potential to revolutionise military operations, for both positive and negative outcomes, for example through the ability to respond as part of routine surveillance operations. This capability however has the potential for severe negative outcomes if left unchecked and international like-minds are working towards appropriate frameworks to govern military swarms, and while allied development may be constrained by ethical considerations, other countries or non-state actors, may not have the same constraints.

These systems offer opportunities across multiple sectors to improve productivity and safety; innovative legal and ethical frameworks and standards to adjudicate human-machine decision making and to manage safety and utility will be required to maximise their potential.

Research Impact (RI)

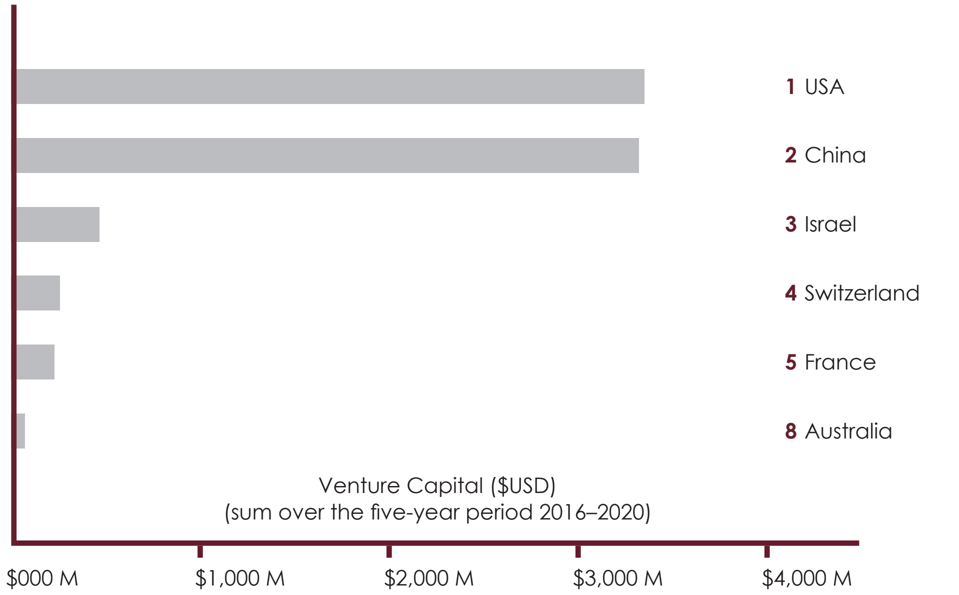
China has the highest research impact, with Australia ranked 9th. Total volume of published research has increased at around 21% p.a. over the 5 year period 2016–2020, with 19% of research involving international collaboration.



The research impact provides an indication of the productivity of a country or institution. Here, productivity was assumed to be represented by the volume of publications (i.e. scholarly output) as an indicator of the resources & facilities, and the level of interest in the publications as an indicator of quality.

VC Investment

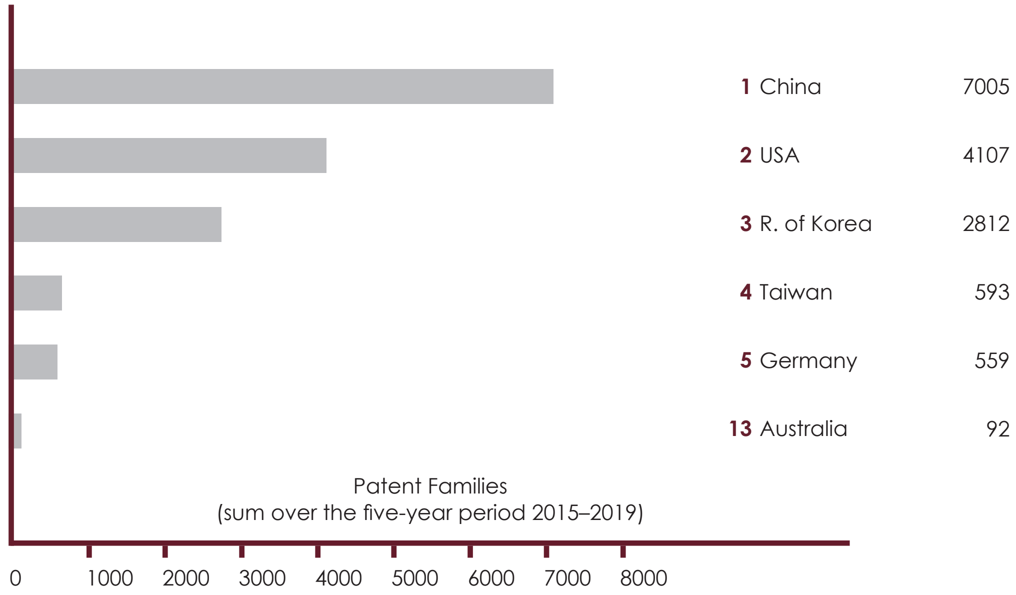
Australia is ranked 8th for relative venture capital (VC) investment for drones and collaborative robotics. Investment in this area has been growing at 10% p.a. since 2016.



Data from Crunchbase. The Crunchbase database provides a partial view of the global VC landscape. However the quantity, quality and richness of the data are considered to be statistically significant, and indicative of global trends.

Patents – International

The number of patents filed annually in this field has increased by 3% p.a. from 2015 to 2019. Most patents for this technology were filed by Chinese applicants or inventors, Australia ranks 13th.



Research Institutions – International

The National University of Singapore has the highest research impact among international institutions. China, which has the highest overall research impact, has 6 institutions in the top 10 international institutions.

Rank	Top International Institution	Research Impact
1	National University of Singapore | Singapore	4797
2	Beihang University | China	3051
3	Virginia Polytechnic Institute and State University | United States	2327
4	Tsinghua University | China	1949
5	Southeast University, Nanjing | China	1863
6	Université Paris-Saclay | France	1778
7	Chinese Academy of Sciences | China	1721
8	Nanjing University of Aeronautics and Astronautics | China	1628
9	French National Centre for Scientific Research (CNRS) | France	1359
10	Northwestern Polytechnical University Xian | China	1316

Research Institutions – Australia

Within Australia, the University of New South Wales has the highest research impact and is ranked 11th internationally. Australia has 4 institutes in the international top 50 – the University of Sydney is 18th, Queensland University of Technology 43rd and University of Technology of Sydney 47th.

Rank	Top Australian Institution	Research Impact
1	University of New South Wales	1216
2	University of Sydney	969
3	Queensland University of Technology	533
4	University of Technology Sydney	515
5	CSIRO	475
6	Royal Melbourne Institute of Technology University	438
7	Monash University	214
8	Deakin University	130
9	University of South Australia	115
10	Australian National University	91

Patents – Australia

Top 3 Australian Patent Applicants	Patent Families
ORBITAL AUSTRALIA	8
DEFENDTEX	2
BHP	2

Patents filed by Australian businesses, 2015–2019.