Australia's National
Science Agency

Growing Australia's Quantum Technology Industry

Positioning Australia for a four billion-dollar opportunity

May 2020

About CSIRO Futures

At CSIRO Futures we bring together science, technology and economics to help you develop transformative strategies that tackle your biggest challenges. As the strategic advisory arm of Australia's national science agency, we are uniquely positioned to transform complexity into clarity, uncertainty into opportunity, insights into action.

Acknowledgement

CSIRO acknowledges the Traditional Owners of the land, sea and waters, of the area that we live and work on across Australia. We acknowledge their continuing connection to their culture, and we pay our respects to their Elders past and present.

The project team is grateful to the many stakeholders who generously gave their time to provide advice and feedback on the Roadmap.

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Foreword

Emerging quantum technology applications will present substantial opportunities for economic growth, improving productivity and creating new jobs in the coming decades. Australia has an exciting quantum ecosystem, full of world-class expertise in many of these game-changing quantum technologies that are poised to revolutionise a range of industries. As Australia's national science agency and innovation catalyst, CSIRO has developed this Quantum Technology Roadmap. This roadmap identifies the enabling actions that can support the quantum ecosystem to transform Australia's intellectual capital into economic value through the growth of a new deep-tech industry for Australia. With sustained investment and collaboration across the sector we can grow our workforce, strengthen translation, and build businesses to generate over $4 billion and 16,000 jobs for Australia by 2040.

This Roadmap showcases only a small selection of the potential paradigm-shifting impacts and benefits that quantum technologies could yield across a range of Australian industries. From defence, to precision measurement, to drug discovery and development, quantum technologies present opportunities to enhance Australia's strengths and develop entirely new capabilities. For example, CSIRO has developed an innovative mineral exploration system using superconducting quantum sensors. The commercial use of these systems has enabled mineral resource discoveries worth billions of dollars over the past 10 years. This is just one small example of the potential value that could be enabled by a national quantum industry.

Australia is currently a strong player in the global quantum technology sector, with world-class expertise and research capabilities developed through over two decades of sustained investment in academic research. This long-term investment in foundational research is now enabling the growth of exciting new start-ups and ventures. These emerging quantum businesses are developing and commercialising diverse offerings including quantum enhanced cybersecurity solutions, quantum computing technologies, precision timing solutions, enabling technologies that support quantum technology development and more.

Coordination and collaboration across the country will be critical to enhance the growth of this industry, which is why this Roadmap has been developed collaboratively with industry, research and government who have contributed through interviews, workshops and responses to a discussion paper. I want to thank all our enthusiastic and insightful contributors – this Roadmap is truly a Team Australia effort. As the quantum technology industry evolves over the coming years, I hope this Roadmap will inform and drive a nationally collaborative and coordinated approach. CSIRO stands ready to support government, industry and research to pursue these opportunities for the benefit of Australia and the world.

Dr Cathy Foley
Chief Scientist
CSIRO
April 2020

Executive summary

Why quantum?

Advanced quantum technologies can create an $86 billion global industry by 2040[1]

In recent years, scientists and engineers have developed unprecedented capabilities to isolate, control and sense individual quantum particles (such as electrons and photons) and their properties. This is underpinning the development of transformational technologies including precision sensors, secure communication networks, and quantum computers. The successful commercialisation of these technologies will create a new high growth industry with the potential to enable decades of economic growth and job creation, and support productivity growth and enhanced security across a range of industries.

Why Australia?

Australia has world class quantum technology research and development capabilities

Australia was a pioneer in quantum technology development and has established world-class quantum research capabilities and expertise through over two decades of sustained research investment. We are now witnessing a growing number of quantum technology related businesses pursuing research and commercialisation efforts in Australia. These includes early stage university spinouts, VC-funded start-ups, joint ventures, and multinationals.

Why now?

The global quantum industry is maturing rapidly as nations invest in technology advancement

Many countries have now recognised the value that will be generated by quantum technology and are investing to prepare their domestic quantum ecosystems for this opportunity. Global capital investment in quantum technology companies grew almost fourfold between 2012 and 2018[2] and the UK, US, EU, India, Germany and Russia have all established billion-dollar scale quantum technology initiatives or funding packages since 2018.[3]

If Australia is to secure its place in this emerging global industry it must act now

To secure its competitive advantages and enable the continued growth of its domestic quantum industry Australia will need to implement a focused and nationally coordinated approach to enhancing its capability, collaboration, and industry readiness. This report explores Australia's opportunity to develop a domestic quantum technology industry, including an assessment of the nation's strengths and challenges, and economic analysis of key opportunity areas for the year 2040. It then describes a series of recommendations that could be undertaken in the short-term to ensure the nation remains strongly positioned to pursue this global opportunity.

1 This figured was developed by CSIRO Futures and uses conservative assumptions. Further, commercial figures do not reflect the total value creation potential of quantum technologies. This would include broader benefits such as gains in productivity, improved national security and indirect industry growth and job creation. Further detail on the economic assessment methodology can be found in Appendix A.

2 Data from Gibney E (2019) Quantum gold rush: the private funding pouring into quantum start-ups. Nature. 574, 22-24. DOI: 10.1038/d41586-019-02935-4

3 See Appendix C for information sources.

A 2040 vision for Australia's quantum industry

VISION: Australia has maintained its globally competitive strengths in quantum technology R&D and developed a sustainable quantum technology industry; generating and owning IP that underpins commercialised applications.

In 2040, Australia's quantum technology industry could generate over **$4B revenue** and **16K new jobs**

Computing
$2.5B
10K jobs

Sensing and measurement
$0.9B
3K jobs

Communications
$0.8B
3K jobs

Quantum technology applications enhance productivity and enable new capabilities in a range of existing industries, including…

Healthcare and medicine

- Quantum sensors enable early disease detection and medical research.
- Quantum computers support accelerated drug development through quantum chemistry simulation.

Defence

- Ultrasensitive quantum sensors detect small signals of interest including magnetic anomalies and trace chemicals.
- Quantum positioning and timing devices enable accurate navigation in GPS-denied environments.

Natural resources

- Quantum sensors enable discovery of valuable ore deposits and efficient groundwater monitoring.
- Quantum computers enhance modelling of complex weather and climate systems.

Financial services

- Quantum computers model and optimise complex systems such as investment portfolios.
- Secure communications are underpinned by key generation and communication using quantum mechanical properties.

Enabling Australia's quantum technology industry

Realising the benefits associated with the 2040 vision will not occur without coordinated action to enable the growth of Australia's quantum technology industry. The following table provides a high-level overview of near-term actions designed to support the long-term success of Australia's quantum technology industry for consideration by stakeholders in Australia's quantum ecosystem. These activities could be commenced immediately, with follow up activities arising as the industry begins to scale. Section 4 of the Roadmap describes these recommendations in greater detail.

FOCUS

Focus and coordinate Australia's quantum industry development efforts.

CAPABILITY

Build Australia's quantum workforce and infrastructure capabilities.

KEY RECOMMENDATIONS FOR CONSIDERATION

Develop a national quantum technology strategy to implement this roadmap's enabling actions and set long-term strategic priorities, commitments and indicators of success for Australia's quantum industry.

Explore efficient and effective funding mechanisms to support the demonstration and commercialisation of quantum technology applications and enable the growth of emerging quantum businesses.

Attract, train and retain the best quantum talent and assess the future quantum technology workforce's skill needs to inform strategic capability development and growth.

Assess the industry capabilities and infrastructure facilities that will be critical to the success of a domestic quantum industry and develop business cases to address any gaps.

ADDITIONAL RECOMMENDATIONS

- Support entrepreneurship and accelerator programs that enhance the commercialisation skills of deep technology start-ups.
- Continue to support and leverage Australia's shared research infrastructure through the National Collaborative Research Infrastructure Strategy to promote open collaboration and cost-effective capital expenditure.
- Enhance research and training linkages between Australian Universities with complementary quantum strengths.
- Proactively explore and address any unknown ethical, social or environmental risks that may arise with the next generation of quantum technologies.

COLLABORATION

Support productive collaboration with local and international partners.

READINESS

Enhance the readiness of governments, society and end-users for next generation quantum technologies.

Establish multidisciplinary and multi-institution projects to demonstrate commercial applications of advanced quantum technologies; and develop software applications and control techniques for noisy intermediate-scale and large-scale quantum computers.

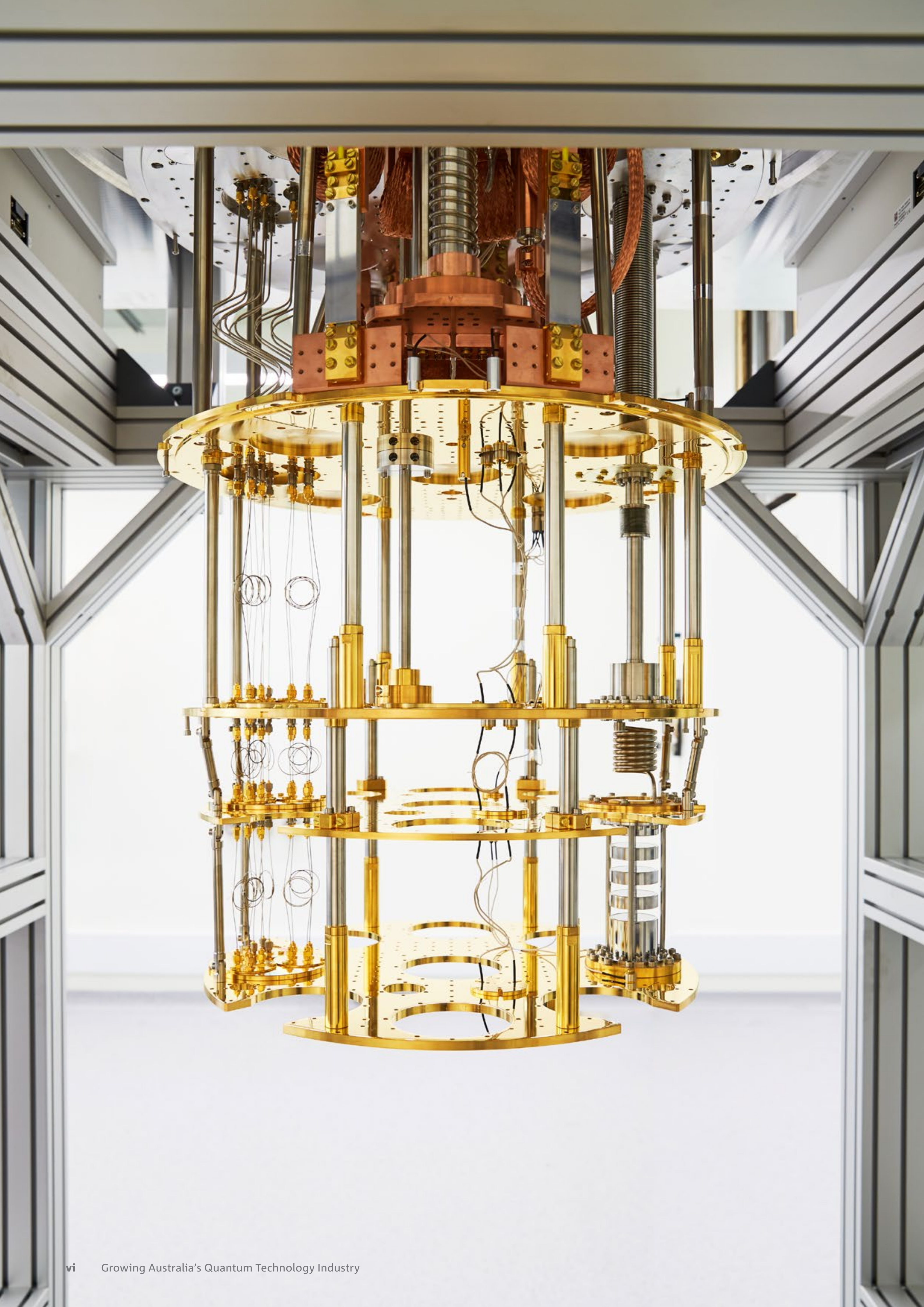
Promote Australia's domestic quantum technology capabilities and explore opportunities to undertake R&D projects with trusted partners.

Provide clarity on the implementation of defence trade control regulations to provide confidence to the industry and ensure that Australia's IP and national security are protected.

Encourage proactive local end-user and government engagement with Australia's quantum ecosystem.

- Undertake a thorough assessment of critical materials and components for quantum technologies.
- Develop strong guidance and standards for the development and deployment of quantum applications.

- Consider encouraging universities to ensure that their IP management practices encourage collaboration, entrepreneurship and commercialisation.
- Enhance domestic capabilities and engage with international efforts to develop post-quantum cryptographic methods.



Contents

Glossary

Acronym / Term	Definition
ARC	Australian Research Council
Classical computing	Classical computing (also known as binary computing) describes conventional computing systems in which information is stored in bits that are represented logically by either a 0 (off) or a 1 (on).
CoE	Centre of Excellence
CQC2T	ARC Centre of Excellence for Quantum Computation and Communication Technology
CRC	Cooperative Research Centre
DTCA	Defence Trade Controls Act
EQUS	ARC Centre of Excellence for Engineered Quantum Systems
PFRA	Publicly Funded Research Agency
PNT	Positioning, Navigation and Timing
QKD	Quantum Key Distribution
Quantum computing	Quantum computers code information in engineered quantum objects called quantum bits. This allows them to represent not only a 0 or a 1 but also a superposition of 0 and 1 at the same time. By taking advantage of this and other quantum phenomena they enable a new form of computation.
Quantum technologies	Technologies that make use of our ability to detect and manipulate single quantum objects (e.g. atoms, electrons, photons) and their properties, such as quantum computing, secure communications, and sensing.
R&D	Research and Development
SME	Small to Medium-size Enterprise

This report

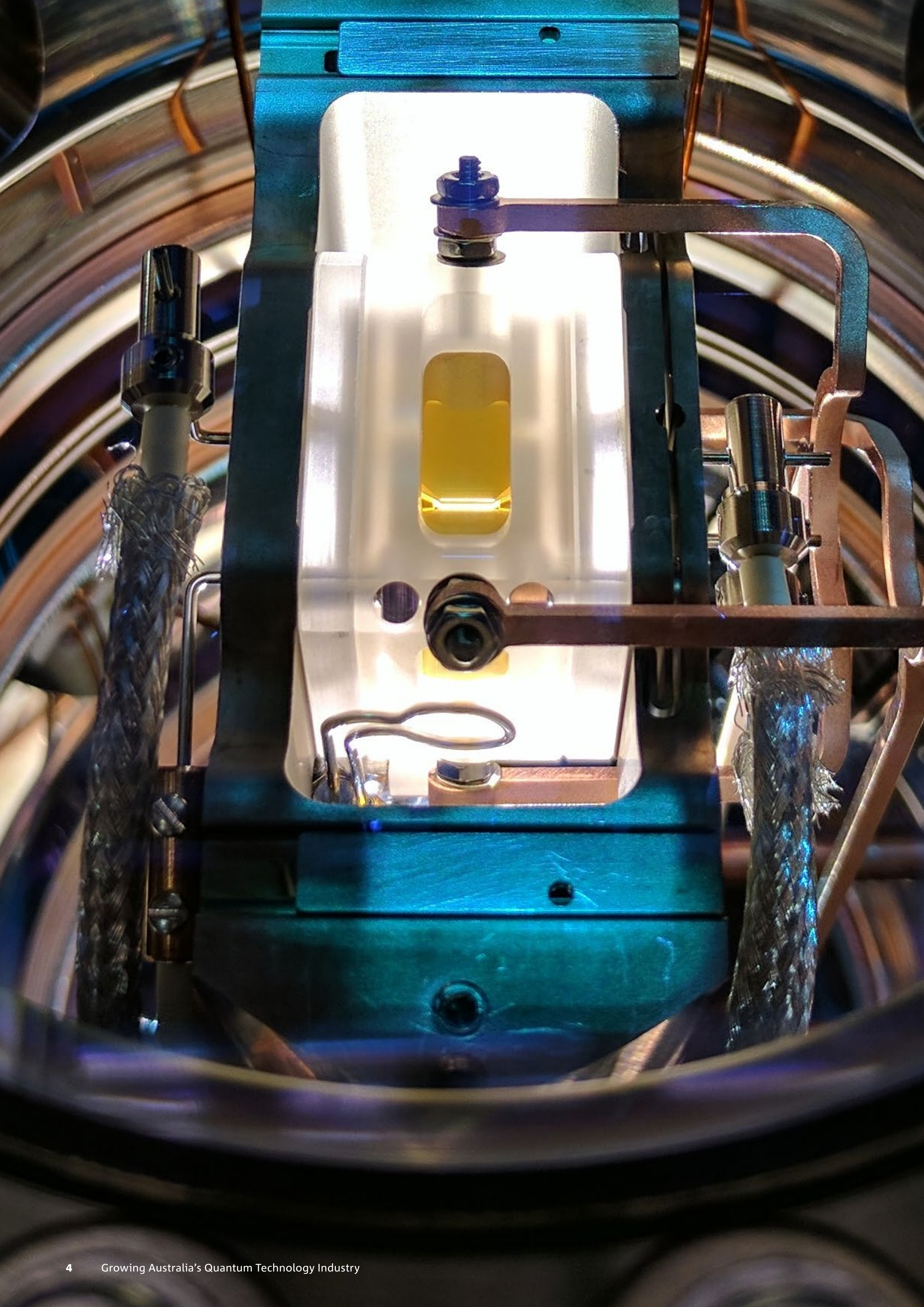
Quantum technology is an area of science and technology that has significant long-term potential for industry growth in Australia. Recognising this, CSIRO has prepared an industry development roadmap to identify a pathway forwards for this emerging industry. This Roadmap:

- explores the rationale for investing in the development of a quantum technology industry
- describes Australia's quantum technology landscape and the challenges that need to be addressed to maximise the emerging industry's chances of success
- conservatively estimates the economic value that could be realised by Australia in 2040 through the successful commercialisation of quantum computing, sensing and communications technologies
- proposes enabling actions to support long-term growth a of a sustainable Australian quantum industry.

The Roadmap is focused on actions that can begin immediately to enable the successful development, demonstration and commercialisation of emerging quantum technologies over the next 20 years.
This Roadmap is primarily focused on advanced quantum technologies that take advantage of uniquely quantum behaviours (also known as second wave quantum technologies), but also considers the enabling software and technologies that are essential to their development and operation. Its primary focus is on technologies that currently sit between technology readiness level three (proof of concept) and seven (full scale demonstration in relevant environments).[4]

This report was developed in consultation with over 80 stakeholders from more than 40 organisations across the quantum technology industry, including representatives from university research groups, publicly funded research agencies (PFRAs), industry, end-users, governments and private investors. Insights were collected through one-on-one interviews, workshops, and formal submissions provided in response to a discussion paper that was released in November 2019.

4 NASA (2012) Technology Readiness Level. Viewed 25 June 2019, <https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html>



1 Why quantum, why now?

Paradigm shifting technologies

The field of quantum physics emerged in the early 20th century and has transformed how the world functions. Impacts include the development of laser technologies that underpinned the creation of the internet, medical imaging technologies, and the transistor and semiconductor technologies that enabled the digital electronics revolution of the 20th century.

As these applications reach their physical limitations, a second wave of revolutionary quantum technologies is now maturing. These new technologies are distinguished from the first wave by the ability to engineer quantum states.[5] Researchers have demonstrated proof of concept for transformational quantum technologies including precision sensors, secure communication networks, and quantum computers. Successful commercialisation of these technologies can underpin industry growth for decades to come while driving productivity growth and enhancing security across a range of existing industries.

Successful commercialisation of quantum technologies can underpin industry growth for decades to come.

Similar to scientists and engineers in the early 1900s who could not predict the impacts of early quantum technologies like the transistor, we cannot predict with accuracy the most disruptive and beneficial applications of quantum technology. However, the long-term impact of advanced quantum technologies could be as significant as the digital electronics revolution. In this Roadmap we focus on examples of applications that are actively being developed, such as:

- accelerated drug and materials development enabled by accurate chemical simulations that run on quantum computers and draw on computation capability not possible on classical computers
- stable and precise sensors for mineral exploration and water resource management
- quantum-enhanced information security for sensitive data and critical infrastructure.

An opportunity for economic diversification and growth

In order to maintain a productive, inclusive and resilient economy over the next 40 years, Australia needs to increase the adoption of technology to boost productivity and develop export-facing growth industries.[6] The development of an Australian quantum technology industry presents a prime opportunity to address these actions as part of a portfolio approach to investment in long-term, high-impact technologies.

A domestic quantum technology industry enabled by Australia's existing world-class quantum research and development (R&D) capabilities can create significant economic value. Quantum technologies can improve productivity and increase the nation's economic resilience through high value-adding industry creation.

5 MacFarlane AGJ, Dowling JP and Milburn GJ (2003) Quantum technology: the second quantum revolution. Philosophical Transactions of the Royal Society of London. DOI: 10.1098/rsta.2003.1227

6 CSIRO (2019) Australian national outlook 2019. CSIRO. DOI: 10.25919/5d126f3ece03d

Accelerated global investment and focus

Global investments in quantum technology have rapidly increased in recent years as private investors, businesses and governments grow more confident in the economic potential of quantum technology. Globally, at least 52 quantum technology companies received capital investment between 2012 and 2018. Over this period, the value of these investments grew almost fourfold (see Figure 1). Private capital investment continued its growth in 2019.[7] These figures do not include the significant undisclosed investments made by large technology companies such as Google, IBM and Microsoft.

Many governments are implementing strategic investment programs to develop their domestic quantum industries. Since 2017, at least 5 nations have committed to billion-dollar scale quantum technology initiatives or funding packages (see Table 1). China is also investing heavily, including a reported $14.7 billion for the world's largest quantum research facility.[8] These national initatives recognise quantum technology as both a valuable long-term investment and an important sovereign capability due to its potential applications in secure communications and defence.

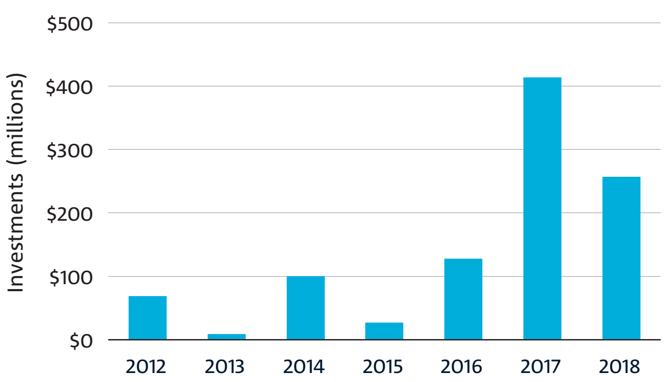


Figure 1. Publicly disclosed capital investments in quantum technology companies (2012-2018)[9]

Quantum technology is both a valuable long-term investment and an important sovereign capability due to its potential applications in secure communications and defence.

Table 1. Public funding commitments for quantum technology commenced since 2017[10]

Commitments	Countries/unions
$1.5–2 billion	EU, India, US
$1–1.5 billion	Germany, Russia, UK
$0.5–1 billion	Netherlands
$<500 million	Australia, Canada, Japan, South Korea, Switzerland

Australia must act now to secure its competitive advantages

Australia established itself as a pioneer in the field of quantum technology R&D though over two decades of targeted research efforts, which are now coming to fruition through the emergence of a variety of quantum technology start-ups. Australia can become an important part of a global quantum industry supply chain, contributing to fundamental scientific knowledge and developing intellectual property and advanced technologies that can be exported and monetised. However, in the context of booming private investment and strategic commitments by its international peers, Australia must act now to build upon its strengths in quantum technology R&D and position itself to capture this opportunity.

7 CSIRO analysis of data provided by PitchBook identified $730 million worth of capital investment in quantum technology companies in 2019. This includes venture capital, private equity, joint venture, and mergers and acquisitions. Note that the method used to collect this data differs from the information presented for the 2012-2018 period and is assumed to be less conservative.

8 Quantum Delta NL (2019) National agenda for quantum technology <https://qutech.nl/wp-content/uploads/2019/09/NAQT-2019-EN.pdf>. At an exchange rate of 1.47 AUD per USD. Morningstar (2019). Currency Data - USD to AUD as at 03/12/2019.

9 Data from Gibney E (2019) Quantum gold rush: the private funding pouring into quantum start-ups. Nature. 574, 22-24. DOI: 10.1038/d41586-019-02935-4

10 See Appendix C for further detail and information sources. Investments have been converted to Australian Dollars. Note that figures here are conservative, restricted to funding which has been reported publicly via substantive sources. The investments listed include only those which have been commenced from 2017 onwards or are confirmed as set to commence in future.

2 Australia's quantum landscape

Australia has built world class quantum technology R&D capabilities over more than two decades and is well placed to play a vital role in the global effort to commercialise quantum applications. A growing number of start-ups and related businesses are undertaking development and commercialisation of quantum technologies.

However, Australia must overcome a number of challenges in order to capitalise on its quantum strengths and enable the long term growth of this emerging industry. Additional details on the key research and industry players in Australia's quantum technology landscape are provided in Appendix B.

Established R&D capabilities

Quantum R&D institutions in Australia

National
- EQUS
- CQC^{2}T
- Exciton Science
- FLEET
- Nanoscale BioPhotonics
- OzGrav
- CSIRO
- Defence Science and Technology

Queensland
- Griffith University
- University of Queensland

New South Wales
- Macquarie University
- UNSW
- University of Sydney
- University of Technology Sydney

Australian Capital Territory
- Australian National University

Victoria
- Monash University
- RMIT University
- Swinburne University
- University of Melbourne

Western Australia
- Curtin University
- University of Western Australia

South Australia
- University of Adelaide

Institution type
- University
- ARC CoE (quantum-focused)
- ARC CoE (quantum-related)
- Public Funding Regulatory Association

22
Quantum-related research institutions around Australia

60%
Higher normalised citation impact than global average

8
Universities performing well above world standard quantum physics research

2
Quantum-focused Centres of Excellence

Figure 2. Australian research institutions active in quantum technologies[11]

11 See Appendix B. Tables 2 and 3 for detailed lists of Australian research institutions active in quantum technologies. 'Well above world standard' is a rating defined by the Australian Research Council against its set of evaluation indicators. https://dataportal.arc.gov.au/ERA/NationalReport/2018/pages/introduction/index.html?id=era-2018-evaluation-process

A pioneer in quantum technology research

Australia has been at the forefront of quantum technology development since the late 1990s, building infrastructure and talent across the industry through Australian Research Council (ARC) programs and enhanced by various defence and industry grants. Due to the pioneering efforts of several leaders in the sector, Australia built strong research capabilities, established proof-of-concept for key technologies, and attracted talent while some countries were still establishing quantum technology research centres. These research efforts have been well funded with the two quantum-technology focused ARC Centres of Excellence (CoEs) receiving over $80 million in funding commitments each from the ARC and participating organisations, as well as significant in-kind support for their activities since 2011. Australia now has a strong quantum technology research base including over 200 researchers participating in each CoE.

World class, impactful research

There are now at least 22 quantum-related research institutions in Australia including eight universities performing quantum physics research well above the world standard, according to evaluation by the ARC.[12] Australia's research sector has led or contributed to important fundamental and applied quantum technology breakthroughs for over more than two the decades. Some examples of Australia's many contributions to the field include blueprints for major quantum computing hardware platforms, the building blocks of silicon and optical-based quantum computing, leading quantum simulation algorithms, designs for quantum communications networks, and critical components for quantum sensing technologies.

Global connections

In recognition of their world class capabilities, Australia's quantum researchers have attracted funding and attention from international stakeholders including Google, Lockheed Martin, IBM, Microsoft,[13] and the US Government.[14] There are several examples of alumni from Australia's research community going to lead quantum research divisions in companies including IBM or found start-ups such as PsiQuantum (US) and Xanadu (Canada) overseas. This global connectivity is an essential enabler of an industry in which successful local efforts are likely to require input and collaboration from global peers, and where sustainable businesses will be established via strong export pathways.

A growing quantum education ecosystem

Education opportunities will be a significant point of differentiation between nations and institutions involved in quantum technologies. Australian universities, centres of excellences, and state and federal governments are investing in education to attract and develop the next generation of talent in quantum technologies. Recognising the need for a workforce with diverse skills, universities are beginning to establish a variety of quantum education offerings including masters programs (e.g. The University of Queensland's Master of Quantum Technology, The Australian National University's Master of Science in Quantum Technology), undergraduate majors (e.g. University of Technology Sydney's Computer Science undergraduates can now major in Quantum Information Science), and even short courses (e.g. The University of Melbourne's short course on quantum information processing).

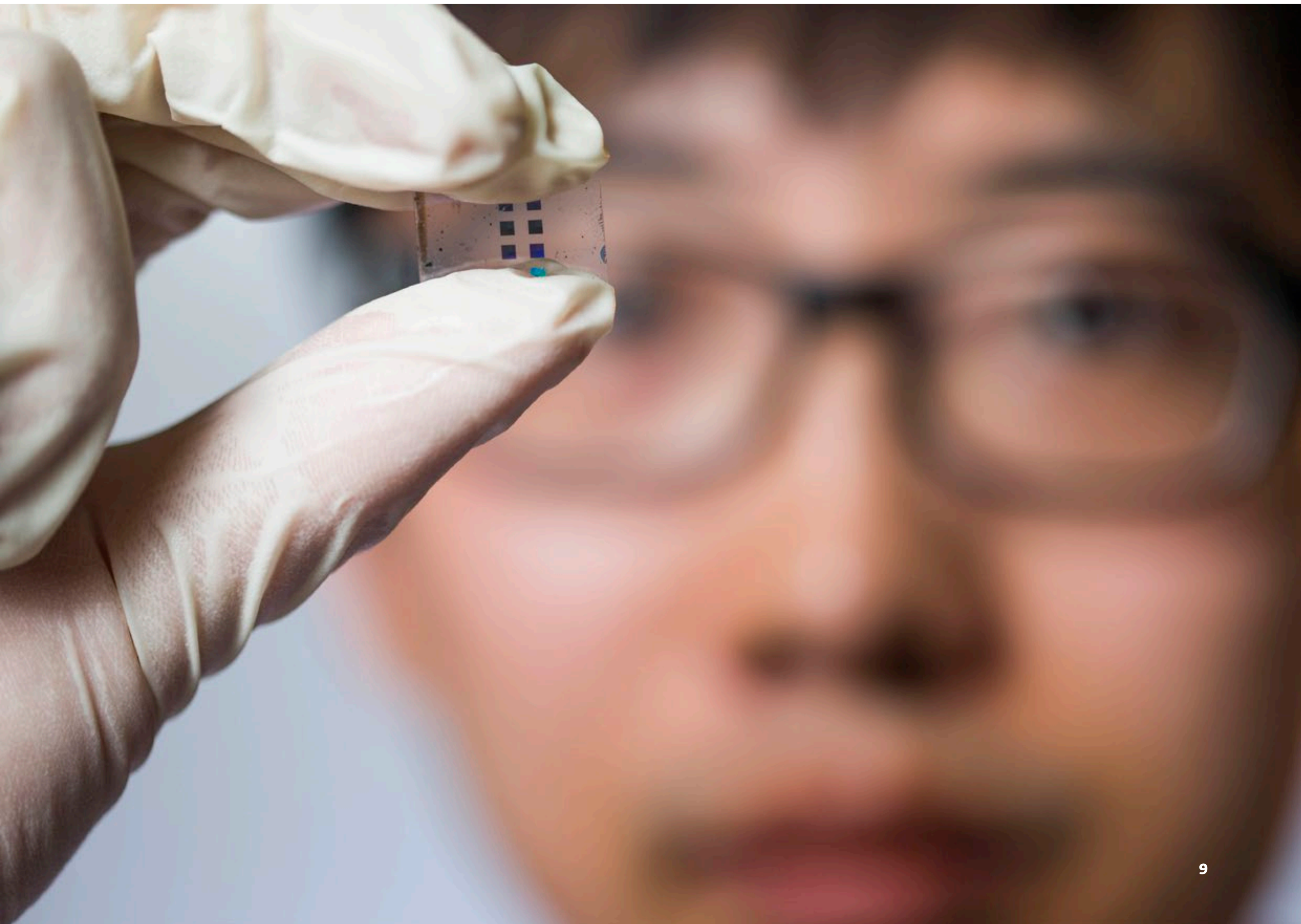
12 Australian Research Council (2019) State of Australian University Research 2018-19. Australian Government. Viewed 29 August 2019, <https://dataportal.arc.gov.au/ERA/NationalReport/2018/>

13 The University of Sydney (2017) Microsoft and University of Sydney forge quantum partnership. Viewed 9 October 2019, <https://sydney.edu.au/news-opinion/news/2017/07/25/microsoft-and-university-of-sydney-forge-quantum-partnership.html>

14 Australian Government (2018) Australian and US universities to collaborate on defence research. Viewed 4 October, <https://www.minister.defence.gov.au/minister/christopher-pyne/media-releases/australian-and-us-universities-collaborate-defence-research>

Sydney Quantum Academy is supporting the development of the next generation of quantum engineers and scientists

The Sydney Quantum Academy (SQA) is a joint initiative by the University of Sydney, University of Technology Sydney, Macquarie University and the University of New South Wales to grow Australia's quantum technology ecosystem. SQA will enable students to collaborate and train between universities; link students and research fellows to industry, through industry internships, research projects and events; support industry engagement and entrepreneurship in quantum fields; and promote Australia as a global leader in quantum computing. The initiative also aims to improve public and business understanding of quantum technology. The NSW Government, partner universities and industry will invest around $35 million in the initiative. SQA demonstrates how targeted investments and collaboration can help Australia's quantum capabilities.

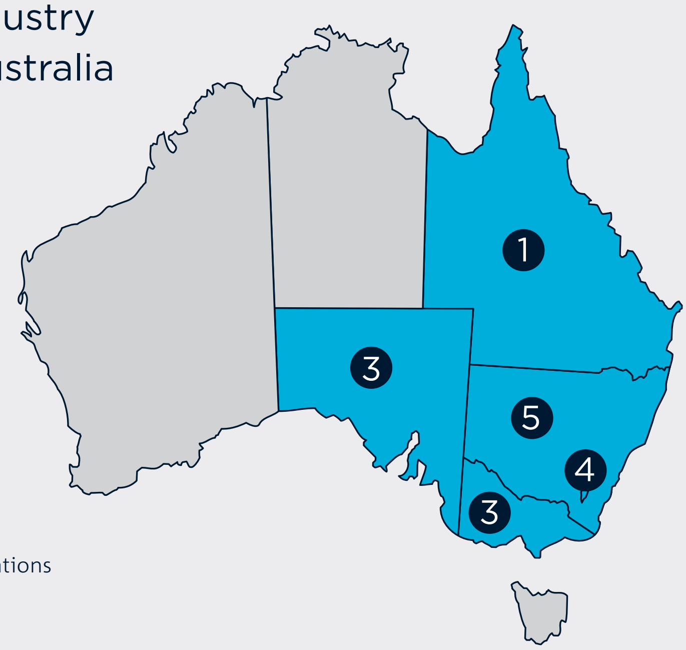


An emerging quantum industry

A growing number of quantum technology start-ups and related businesses are undertaking their development and commercialisation efforts in Australia. Australia's leading quantum technology companies QuintessenceLabs (over $30 million), Silicon Quantum Computing ($83.7 million), and Q-Ctrl (over $22 million) have each attracted significant investment and funding.

QuintessenceLabs has commercialised a variety of quantum-enhanced cybersecurity solutions; Silicon Quantum Computing has developed record-breaking silicon-based qubits and plans to build a 10-qubit prototype quantum-integrated processor by 2023;[15] and Q-CTRL has released a hardware-agnostic software suite to enhance quantum technology stability.

Quantum industry activity in Australia



Quantum sectors

- Quantum computing
- Quantum sensing
- Quantum communications
- Consultancy
- Enabling technology

Queensland
- Max Kelsen

New South Wales
- Microsoft (US)
- Silicon Quantum Computing
- Redback Systems
- Lucigem
- Q-CTRL

Australian Capital Territory
- Quantum Brilliance
- Nomad Atomics
- QuintessenceLabs
- Liquid Instruments

Victoria
- IBM (US)
- h-bar Consultants
- MOGlabs

South Australia
- Archer
- Rigetti Computing (US)
- Cryoclock

16 Quantum-related private organisations around Australia

$125m+ Funding and investment (2017–2019)

Figure 3. Private organisations active in quantum technologies in Australia[16]

15 Silicon Quantum Computing (2020) About. <https://sqc.com.au/>
16 See Appendix B. Table 4 for detailed list of active companies in Australia

All these ventures are built upon IP and skills developed in Australian research institutions. There are also new start-ups emerging that seek to demonstrate and commercialise knowledge that was developed within the Australian quantum industry. For example, in 2020, CSIRO's ON Accelerate Program is supporting three quantum-related teams to develop and validate their business models: Nomad Atomics (a precision accelerometry and gravimetry sensing platform for monitoring underground resources such as water and gas); Quantum Brilliance (a diamond-based quantum computing platform); and Redback Systems (a compact spectrograph with higher resolution imaging).

Some international companies have also established a local presence. For example, Rigetti Computing has a quantum computing applications development team working in Australia, and Microsoft has established a quantum computing research partnership with the University of Sydney.

Challenges to overcome

There are several challenges and risks that may restrict the growth of the quantum technology industry. Many of these are not unique to Australia but all are important to consider when making decisions and investments related to quantum technology. Overcoming these challenges and risks will help to build competitive advantage in the development of Australia's quantum technology industry.

Fragmented strategy

As a nation, Australia is yet to articulate a long-term strategy and clear investment priorities for the quantum technology industry. Federal and state governments have made valuable investments and established important initiatives, however the piecemeal approach to industry development contrasts with the US, UK, EU, and China which have all established national strategies supporting quantum technology development. A national industry development strategy will improve the effectiveness of initiatives to develop Australia's quantum capabilities.

Global competition for talent

As other nations and international companies scale their quantum technology efforts, competition for talent has become increasingly intense. The quantum technology industry requires a highly skilled workforce with diverse capabilities including quantum-related R&D, hardware and software engineering, precision manufacturing and nanofabrication, technology commercialisation and business skills. Ensuring that Australia can attract, develop and retain talent in these areas will be essential.

Australia's quantum capabilities are often built around the deep-domain expertise of a limited number of experts[17] and there are already several examples of researchers leaving Australia to lead quantum research divisions and start-ups overseas.[18] Creating an environment that supports Australia's quantum experts to continue creating impact can minimise the risk of brain drain from this sector. Stakeholders also mentioned instances of international students and researchers turning down offers after lengthy delays in securing the appropriate visa. It will be important to reduce barriers to efficient recruitment of global talent to support the short-term growth of the domestic quantum industry.

Infrastructure availability

Quantum technology development and fabrication is capital intensive and expensive. Australia has established globally competitive research fabrication infrastructure through the Australian National Fabrication Facility (ANFF), but these facilities are not designed to enable scale-up pilot manufacturing of such precise devices.[19] As such, Australian start-ups and research groups can face difficulties in accessing the infrastructure required for device prototyping and fabrication. Australia's size and geographic dispersion increases the risk of fragmentation and underinvestment in equipment and infrastructure relative to international peers. Investing in world class infrastructure facilities and the skilled people to operate them will be essential for Australia to build upon its quantum R&D strengths and expand its ability to prototype and test quantum technologies.

17 Despite Australia's strong quantum R&D capabilities there are some areas where Australia has limited capacity. For example, Australia only has a small number of researchers with expertise on two of the dominant quantum computing physical architectures: trapped-ion and superconducting.

18 Roberson TM and White AG (2019). Charting the Australian quantum landscape. DOI: 10.1088/2058-9565/ab02b4

19 At present, the ANFF network provides Australia's quantum industry with access to micro and nano-fabrication infrastructure for research and prototyping. Australian Government (2016). National Research Infrastructure Roadmap. Viewed at < https://docs.education.gov.au/system/files/doc/other/ed16-0269_national_research_infrastructure_roadmap_report_internals_acc.pdf>

Critical material and component supply

Supply shortages for specialised materials and components used in quantum technologies can create costly delays, slow commercialisation activities and inhibit scalability of operations. It will be important for developers of quantum technologies to proactively engage with their supply chains and identify and address areas of risk. This challenge also presents a potential opportunity for Australian industry to supply critical inputs into the global quantum technology supply chain.

Turning a challenge into an opportunity

Aware of the need to secure and diversify supply of Silicon-28, an isotope of silicon critical in the development of stable silicon qubits, Silicon Quantum Computing (SQC) recently entered into an offtake agreement with Silex Systems. This agreement will support the development of a process for the commercial production of high-purity Silicon-28 using Silex System's laser isotope separation technology and provide both SQC and Silex Systems with certainty around the sale and purchase of the Silicon-28 product.[20]

In a similar vein, the University of Melbourne received over $1 million funding from select universities and the ARC to establish and administer a National Facility for Quantum Diamond in 2019, which aims to provide tailored isotopic diamond materials for the Australian quantum technology community.[21]

Barriers to research commercialisation

Assessments of Australia's innovation system have found that Australia performs well at knowledge creation but has a poor record on the transfer and application of this into new technologies and businesses.[22] Consultations suggested that key challenges for a quantum technology industry include, poor end-user awareness of quantum technologies, limited commercial skills among many researchers and conservative university intellectual property (IP) management practices hindering local commercialisation of university-owned research. Further, Australian industry and investor risk aversion to deep technology R&D investment was cited as a barrier that can lead researchers and start-ups to look for opportunities and funding overseas. Targeted efforts to support the quantum industry, and broader reforms to support research translation and commercialisation will help capture the full value of Australia's quantum technology IP.

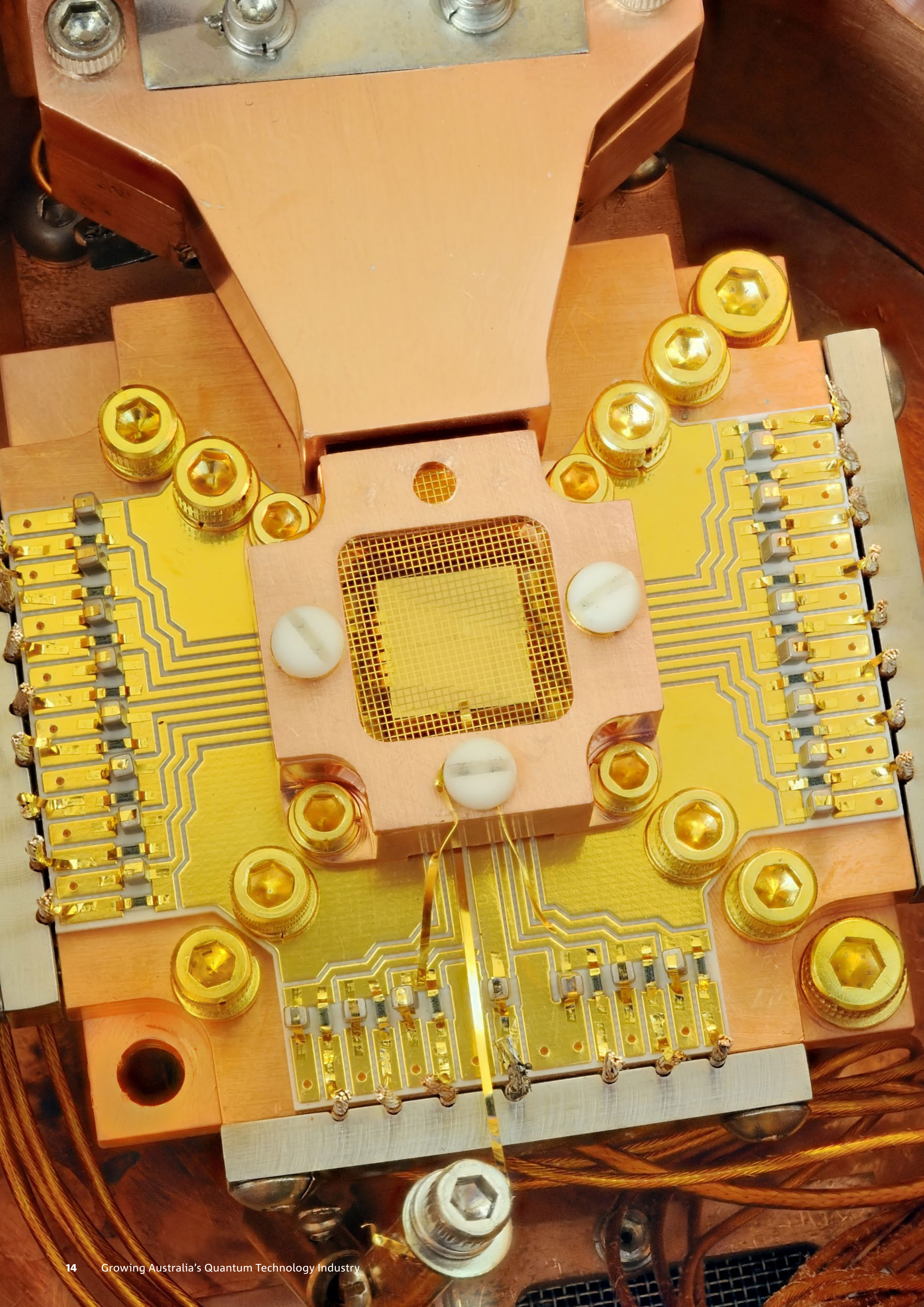
National security

The development of quantum technologies for secure communications, defence applications, and codebreaking is expected to have implications for national security. Developing Australia's sovereign quantum technology capabilities will ensure that the country is prepared for the challenges and opportunities this presents. Australia's Defence Trade Controls Act plays a vital role in protecting Australia's IP and national security, however many of the consulted stakeholders expressed concerns that heavily restrictive controls to mitigate national security risk have the potential to stifle research collaboration and business growth. An ongoing dialogue between stakeholders will be essential to ensure that the research and industry community are well informed about relevant information and industrial security risks, and that trade control regulations are fit for purpose and commensurate with risk.

20 Silex Systems Limited (2019) Silex and Silicon Quantum Computing Pty Ltd Launch Silicon Enrichment Project for Quantum Computing. <http://www.silex.com.au/Silex/media/Corporate-Governance/12-SLX-Silicon-Enrichment-Project-with-SQC-Pty-Ltd-121219.pdf?ext=.pdf>

21 Australian Research Council (2019) Minister's Approval for Linkage Infrastructure, Equipment and Facilities for Funding Commencing in 2020 Schedule. <https://www.arc.gov.au/file/11177/download?token=Bt498qK7>

22 Innovation and Science Australia (2016) Performance Review of the Australian, Science and Innovation System. <https://www.industry.gov.au/sites/default/files/2018-10/performance-review-of-the-australian-innovation-science-and-research-system-isa.pdf>



3 Australia's opportunity

Conservative estimates suggest that the successful commercialisation of emerging quantum technologies could be worth at least $86 billion globally by 2040.[23] If Australia captures a share of this market proportional to its quantum research investment and workforce, it would generate more than $4 billion of revenue and create 16,000 new jobs by leveraging its strengths and developing a globally connected and sustainable quantum industry. This is comparable to recent estimates of Australia's wool ($3.6 billion, 2016-2017) and wheat ($5.8 billion, 2017-2018) industries.[24,25]

Emerging quantum technologies could be worth at least $86 billion globally by 2040.

This section of the Roadmap outlines a vision for Australia's quantum industry towards the year 2040 and describes the value that can be created through commercial applications of quantum computing, sensing, and communications technologies. The successful development of these technologies has the potential to create a high growth industry for decades to come while enhancing productivity growth across a range of existing industries. In addition to direct economic growth and job creation, development of a quantum technology industry can enable other benefits including export diversification, productivity gains across a range of industries, and sovereign capability for enhanced national security.

In the long-term, there will be significant value created by diverse quantum hardware and software technologies, and the products and services they enable. To capture this value, Australia quantum businesses will need to engage with global supply chains and define areas of focus where they can compete on a global scale. Capturing near-term opportunities will also be essential to provide early revenue streams and enable industry growth. These include the commercialisation of applications and instruments for organisations in quantum technology R&D, and the provision of enabling services including education and training, and advisory services for companies and governments seeking to explore the opportunities offered by quantum technologies.

The examples of emerging quantum technology applications and activities provided in this section of the Roadmap are far from exhaustive and there remains uncertainty about which quantum technologies will deliver market-dominating applications. Australia's quantum sector has world class expertise in a broad range of quantum technologies, and with the appropriate support will be well placed to identify and commercialise these applications. Coordinated and sustained action will be critical to secure Australia's opportunities and enable the growth of a valuable and impactful industry.

23 The global and Australian commercial opportunity estimates presented in this report have been developed by CSIRO Futures. These estimates were developed under conservative assumptions based on published data sets and stakeholder consultations but are subject to high degrees of uncertainty. Furthermore, commercial figures do not reflect the total value creation potential of quantum technologies. This would include broader benefits such as gains in productivity, improved national security and indirect industry growth and job creation. Further detail on the economic assessment methodology can be found in Appendix A.

24 Department of Agriculture, Water and the Environment (2020) Meat, wool and dairy. <https://www.agriculture.gov.au/ag-farm-food/meat-wool-dairy>

25 Department of Agriculture, Water and the Environment (2020) Grain farms. <https://www.agriculture.gov.au/abares/research-topics/surveys/grains#productivity>

A vision for an Australian quantum industry

VISION: Australia has maintained its globally competitive strengths in quantum technology R&D and developed a sustainable quantum technology industry; generating and owning IP that underpins commercialised applications.

This industry could consist of:

- Several mid-sized and globally competitive quantum technology companies facilitating a thriving quantum ecosystem.
- A world-class quantum workforce applying their diverse skills to the commercialisation of quantum technology and software, with broader benefits through transferable skills and productivity gains.
- National quantum technology and flexible fabrication facilities that enable collaborative R&D, engagement with end-users, and product prototyping for global value chains.
- A strengthened quantum research sector that continues to contribute to cutting edge quantum research and development, generating valuable knowledge and IP for the quantum industry.

In 2040, Australia's quantum technology industry could generate over **$4B revenue** and **16K new jobs**

Computing
$2.5B
10K jobs

Sensing and measurement
$0.9B
3K jobs

Communications
$0.8B
3K jobs

Quantum technology applications enhance productivity and enable new capabilities in a range of existing industries, including...

Healthcare and medicine

- Quantum sensors enable early disease detection and medical research.
- Quantum computers support accelerated drug development through quantum chemistry simulation.

Defence

- Ultrasensitive quantum sensors detect small signals of interest including magnetic anomalies and trace chemicals.
- Quantum positioning and timing devices enable accurate navigation in GPS-denied environments.

Natural resources

- Quantum sensors enable discovery of valuable ore deposits and efficient groundwater monitoring.
- Quantum computers enhance modelling of complex weather and climate systems.

Financial services

- Quantum computers model and optimise complex systems such as investment portfolios.
- Secure communications are underpinned by key generation and communication using quantum mechanical properties.

3.1 Quantum computing

Quantum computers have the potential to contribute to industry growth by enabling productivity improvements in diverse industries including pharmaceuticals, material design, defence, finance, energy, and engineering.

$2.5B p.a.

10,000 new jobs

Quantum computers code information in the properties of carefully engineered quantum systems called quantum bits (qubits) and take advantage of quantum phenomena to create a new form of computation. The development of quantum computing offers potential to solve a variety of problems that are intractable on classical computing systems.

Example applications include:

- **Accelerating drug and advanced materials development through chemistry simulation:** The design of new molecules and materials typically involves the testing of many different molecules for desired properties. This process is time consuming and costly, and it can be faster to use simulation instead. Quantum computers have already been used to model simple molecules (e.g. water[26]) and as their size and stability increases, they will be able to simulate complex molecules that cannot be modelled using classical supercomputers. This application could accelerate drug design and be used to develop more efficient and sustainable industrial processes (e.g. fertiliser production[27]) and materials.
- **Accelerating machine learning and optimisation of complex systems:** As quantum computers become more powerful they will be able to perform feature mapping, a critical component of machine learning on data structures with a complexity beyond the capabilities of modern classical computers.[28,29] Quantum computing could also be beneficial for complex system optimisation problems, in contexts such as financial modelling, aerofoil design, traffic management, integrated circuit design, climate predictions, epidemiology and energy systems optimisation.

These application examples are far from exhaustive. Researchers and start-ups around the world are searching for breakthrough applications for the error-prone small-to-intermediate scale quantum computers that are currently being developed. Rigetti Computing[30] and Airbus[31] are running competitions to accelerate the demonstration of a quantum computing advantage, with both competitions featuring Australian researchers on their advisory boards.

26 IonQ (2019) Press release: IonQ performs the first quantum computer simulation of the water molecule. Viewed 27 February 2020, <https://ionq.com/news/february-26-2019>

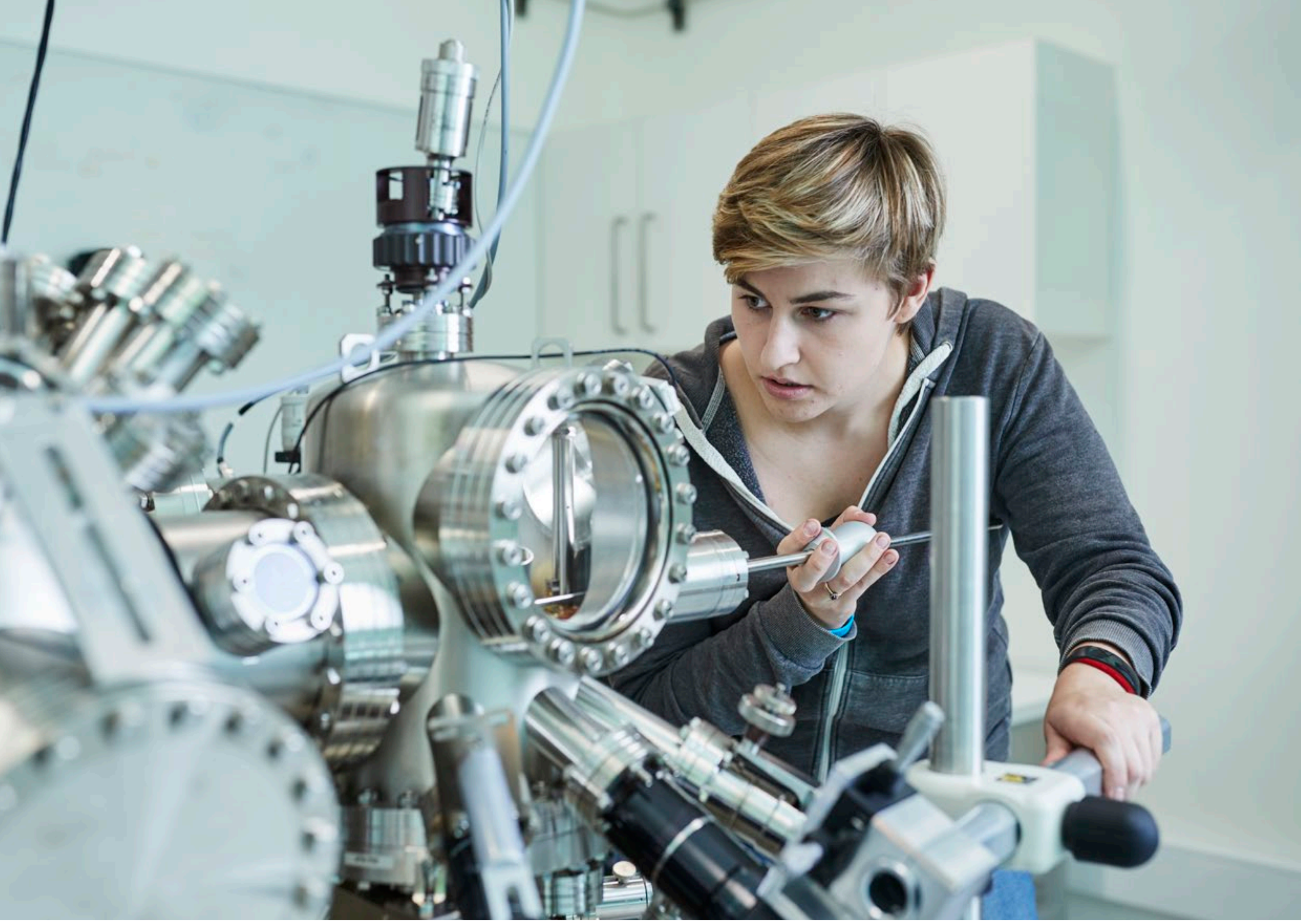
27 Berry D et al. (2019) Qubitization of Arbitrary Basis Quantum Chemistry Leveraging Sparsity and Low Rank Factorization. Quantum 3, 208 (2019). DOI: 10.22331/q-2019-12-02-208

28 Temme K and Gambetta J (2019) Researchers put machine learning on path to quantum advantage. IBM Research Blog. Viewed 27 February 2020, <https://www.ibm.com/blogs/research/2019/03/machine-learning-quantum-advantage/>

29 Havlíček, V, Córcoles A D, Temme K, et al. (2019) Supervised learning with quantum-enhanced feature spaces. Nature 567, 209–212. DOI: https://doi.org/10.1038/s41586-019-0980-2

30 Rigetti Computing (2018) The Rigetti Quantum Advantage Prize. <https://medium.com/rigetti/the-rigetti-quantum-advantage-prize-8976492c5c64>

31 Airbus (2019) Airbus Quantum Computing Challenge. <https://www.airbus.com/innovation/tech-challenges-and-competitions/airbus-quantum-computing-challenge.html>



Australia's opportunity

Australia has strong research capabilities in quantum hardware development and quantum information science, both of which are critical to the development of the hardware and software stack needed to enable functional quantum computing applications. The country is already home to world leading ventures undertaking development of silicon-based quantum computing technology (Silicon Quantum Computing Pty Ltd) and providing quantum control engineering solutions (Q-CTRL). Australia has also attracted key international players including Microsoft and Rigetti Computing who have both established a local presence to take advantage of Australia's quantum capabilities. The US Army Research Office has also been a notable funder of Australian quantum computing research over the past 20 years. Some Australian businesses are also beginning to explore the potential applications of quantum computers to their future operations. These include the Commonwealth Bank of Australia and Telstra (which are both investors in Silicon Quantum Computing) and Woodside Energy (which has become a member of IBM's quantum computing network).

If Australia can capture 5% of the estimated addressable market for quantum computing in 2040, it could generate $2.5 billion in revenue. Australia's quantum computing industry could create 10,000 jobs under this scenario as well as contributing to indirect job creation via flow-on demand and productivity gains. The successful commercialisation of quantum computing technologies can also:

- **create global economic value** by enabling new products, optimisations and productivity gains in industries such as materials (with an estimated global growth potential of $32B), finance ($43B), pharmaceuticals ($42B) and computational fluid dynamics ($22B) by 2050[32]
- **enhance environmental and social outcomes** such as energy savings from more efficient computation, better health outcomes through improved drug design using quantum simulation, more environmentally friendly chemicals development, and safer materials.

32 Boston Consulting Group (2019). Where Will Quantum Computers Create Value and When? Accessed at <https://www.bcg.com/en-au/publications/2019/quantum-computers-create-value-when.aspx>. Economic value is reported as potential incremental operating income enabled by the application of quantum computing technologies. Reported estimates on this page are based on the average of BCG's broad quantum advantage and full-scale fault tolerance forecast scenarios and converted to Australian dollars at an exchange rate of 1.47 AUD per USD.

Case studies

Silicon Quantum Computing is developing a quantum computer based on world leading intellectual property

SQC is developing a 10-qubit quantum integrated circuit prototype in silicon intended for completion by 2023, a forerunner to a silicon-based quantum computer. Its work is based on IP developed at CQC2T, which produced many technology breakthroughs including pioneering globally unique technologies to manufacture qubits at the atomic-scale to realise the fastest two-qubit gate in silicon; lowest noise silicon devices; and highest fidelity qubits in the solid state. SQC is a joint venture by the Australian Government, NSW State Government, the University of New South Wales, the Commonwealth Bank of Australia and Telstra, with initial funding of around $83 million.

Q-CTRL offers software solutions to help solve quantum noise and decoherence challenges in quantum technologies

Sydney-based company Q-CTRL provides hardware-agnostic advanced quantum control solutions for quantum technologies including quantum computing and quantum sensing. The company emerged from research undertaken in the University of Sydney's Quantum Science Group and offers a variety of tools that help improve the utility and error robustness of quantum hardware and algorithms – some of the biggest challenges faced in the field. Q-CTRL is Australia's first VC-funded quantum start-up with over $22 million raised from local and international investors.

Quantum Brilliance is using diamonds to develop room temperature quantum computing hardware

Founded in 2019 by ANU researchers, Quantum Brilliance is using nitrogen-vacancy defects in diamond to build quantum microprocessors which can operate at room temperature. As most quantum computers operate at close to -273°C, this approach could reduce the complexity and energy consumption of quantum computing. Quantum Brilliance is currently developing a few-qubit quantum testbed designed to enable research and innovation in quantum computing and sensing.

3.2 Quantum sensing

Quantum-enhanced precision sensing, metrology, navigation and timing technologies can be applied in diverse industries including resource management, infrastructure, defence, engineering, medical research, healthcare.

$940M p.a.

2,900 new jobs

Researchers have demonstrated the ability of engineered quantum systems to enable precision sensing, metrology, navigation and timing applications. These quantum sensing technologies can enable new capabilities or enhanced performance (e.g. size, weight, power, noise, sensitivity, stability) when compared to existing precision sensing technologies.

Many quantum sensing technologies have demonstrated their potential in laboratory settings and are expected to be less technically challenging than quantum computing. However, in many cases these technologies are entering competitive markets for precision sensing applications. Engagement with end-users to ensure that quantum sensing technologies are engineered to provide practical new capabilities or a significant competitive advantage over existing technologies will be essential.

Example applications include:

- **Precision navigation for defence and civilian applications:** Quantum-enhanced technologies including accelerometers, magnetometers and clocks can enable precision positioning, navigation and timing (PNT) in Global Positioning System (GPS)-denied environments such as underground or underwater. For example, UK-based researchers have suggested that quantum accelerometers could reduce drift in internal submarine navigation systems by a factor of 1000.[33]
- **Quantum gravimetry for sensing of underground environments**: Gravimeters measure differences in the force of gravity and are used to better understand many geophysical phenomena.[34] Quantum gravimeters make use of supercooled atoms to achieve greater sensitivity, stability, and accuracy and could enable faster and cheaper surveys. Potential applications include groundwater mapping, underground leak detection, and early warnings for earthquakes.[35,36]
- **Quantum sensing and imaging devices for early disease detection and medical research:** Quantum-enabled medical imaging technologies could provide enhanced capabilities for the early detection of diseased tissue states. Quantum microscopes can enable nano-scale sensing and imaging at the atomic scale with emerging applications including medical research and nanomaterials development.[37,38]

33 Marks P (2014) Quantum positioning system steps in when GPS fails. New Scientist. 14 May 2014. <https://www.newscientist.com/article/mg22229694-000-quantum-positioning-system-steps-in-when-gps-fails/>

34 Van Camp M, et al. (2017) Geophysics from Terrestrial Time-Variable Gravity Measurements. Reviews of Geophysics, 55(4). DOI: 10.1002/2017RG000566

35 NSW Smart Sensing Network (2019) ANU at the nexus of smart sensing. Viewed 27 February 2020, <https://www.nssn.org.au/news/2019/9/28/anu-at-the-nexus-of-smart-sensing-research>

36 Keesey L (2018) NASA-industry team creates and demonstrates first quantum sensor for satellite gravimetry. NASA. Viewed 3 March 2020, <https://www.nasa.gov/feature/goddard/2018/nasa-industry-team-creates-and-demonstrates-first-quantum-sensor-for-satellite-gravimetry>

37 UK Government Office for Science (2016) The Quantum Age: technological opportunities. <https://www.gov.uk/government/publications/quantum-technologies-blackett-review>

38 Doherty M (2016) The quantum microscope. Australian Optical Society News, 30(2). <http://www.optics.org.au/news/4253081>

Australia's opportunity

Australia has strong capabilities in quantum and precision sensing technology research. The nation has also commercialised some quantum-enabled sensing and measurement technologies based on IP developed in Australian research organisations. These include CSIRO's LandTEM system (a portable magnetic sensor for detection of mineral deposits deep underground) and CryoClock (a cryogenic sapphire oscillator technology for ultra-precise timing applications such as communications and quantum computing).

Australia could generate $940 million revenue if it can 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. The successful deployment of quantum-enhanced sensors in key industry verticals can also:

- **contribute to global knowledge capital** by enhancing metrology and sensing applications in research
- **enhance health and environmental outcomes** through the deployment of improved medical imaging capabilities and monitoring of natural resources
- **support national security** through development of sovereign advanced sensing and PNT capabilities.

Case studies

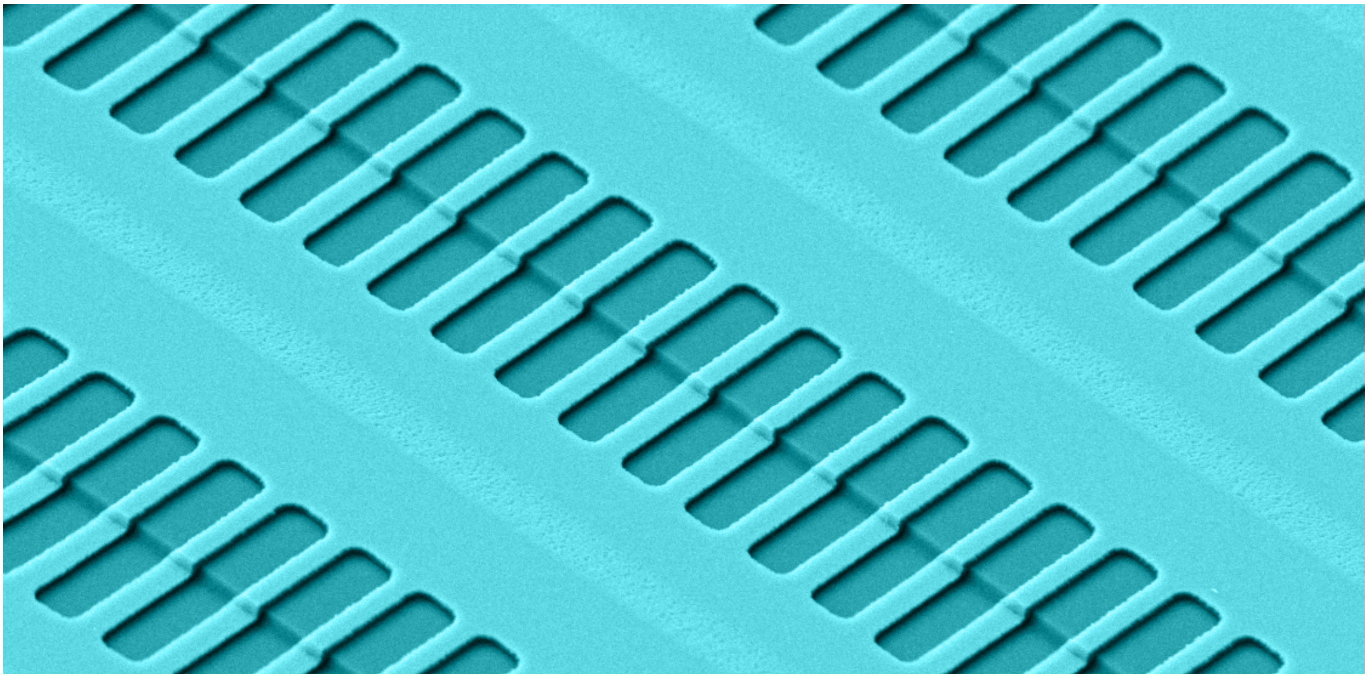
Enhanced quantum sensors for gravity wave observation are enhancing our understanding of the natural world

Kilometre scale laser interferometers, such as the Laser Interferometer Gravitational-wave Observatory (LIGO), allow the detection of gravitational waves caused by events such as colliding black holes and neutron stars.[39] The performance of these interferometers is limited by the presence of quantum noise – tiny fluctuations that cannot be removed. In 2019, LIGO installed Optical Parametric Oscillators based on technology prototyped at the ANU that help avoid quantum noise.[40] This increased LIGO's detection range by 15% (with further improvements expected).[41]

39 Abott BP, et al. (2016) Observation of Gravitational Waves from a Binary Black Hole Merger. Phys. Rev. Lett. 116, 061102. DOI: 10.1103/PhysRevLett.116.061102

40 Chua SSY, et al. (2011) Backscatter tolerant squeezed light source for advanced gravitational-wave detectors. Optics Letters, 36(23). DOI: 10.1364/OL.36.004680

41 ANU (2019) A quantum leap that's been decades in the making. <https://www.anu.edu.au/news/all-news/a-quantum-leap-that's-been-decades-in-the-making>



Quantum magnetometer sensors for discovery of new mineral deposits

The development of quantum-enabled precision sensors to aid mineral exploration presents a valuable opportunity for Australia. Around 70% of Australia features geological cover material that can obscure ore-deposits and create challenges for mineral exploration.[42] CSIRO's LANDTEM system uses superconducting quantum interference devices to detect mineral ore through cover and at greater depths than conventional magnetometers. These systems have been in commercial use for over a decade and have enabled discoveries worth billions of dollars.[43]

Demonstrating defence applications of quantum technology

Quantum technologies are a priority area of the Defence Science and Technology Group Next Generation Technologies Fund, and Australian researchers are investigating quantum technologies for a variety of defence applications. In aligned efforts, the NSW Defence Innovation Network is funding multi-institution teams to prototype quantum devices for defence. The program has identified nitrogen vacancy diamonds for magnetometry applications and single photon emitters for secure quantum communications as priority technologies.[44]

42 Uncover Australia (n.d.) Uncover Australia. Viewed 3 March 2020, <https://www.uncoveraustralia.org.au/>

43 CSIRO (2019) Unearthing mineral deposits around the world. Viewed 27 February 2020, <https://www.csiro.au/en/Research/MF/Areas/Innovation/Superconducting/LandTEM>

44 Defence Innovation Network (2020) Call for proposals: NSW Defence Industry Quantum research Consortium. Viewed 2 March 2020, <https://defenceinnovationnetwork.com/nsw-defence-industry-quantum-research-consortium/>

3.3 Quantum communications

Quantum communication networks and cybersecurity technologies have potential applications in diverse industries including telecommunications, finance, health, government, defence, infrastructure and space.

$820M p.a.

3,300 new jobs

Quantum-enhanced communications systems have potential to advance data, communications and computer security beyond current limitations and enable networking of quantum devices for enhanced utility. Investment in quantum communication networks and related cybersecurity solutions can be expected to grow as the next generation of quantum technologies emerge.

Example applications include:

- **Quantum-enhanced information security systems:** One of the most mature quantum technologies is Quantum Key Distribution (QKD), in which cryptographic keys are shared in quantum states. As measuring a quantum system disturbs it, attempts to intercept the key will introduce detectable anomalies. This makes it possible to detect the presence of a third party attempting to detect the key. QKD is currently more expensive than classical alternatives but could offer stronger communications security for sensitive data (e.g. financial, medical), communications (e.g. defence) and critical infrastructure and will be resilient to quantum computing codebreaking algorithms.[45,46]
- **Quantum-safe cryptography:** A major concern related to the development of a largescale errorcorrected quantum computer is its projected ability to break modern public key encryption standards using a factoring method, known as Shor's Algorithm. Quantum-safe (also known as post-quantum and quantum-resistant) classical encryption algorithms are being designed to resist quantum computing-enabled codebreaking attacks and will be essential for the future security of non-quantum communication systems. The US National Institute of Standards and Technology (NIST) is currently leading a global effort to evaluate and standardize quantum-resistant public-key cryptographic algorithms. Experts are currently divided on whether these algorithms will complement or disrupt the opportunity for QKD in the long-term.
- **Building a quantum internet:** Developing a quantum internet able to network quantum devices will be essential to unlock some of the possibilities of quantum technology, such as scalable networks of quantum sensor networks and distributed quantum computing. Building these networks will require the development of a range of quantum technologies and digital infrastructure including an optical communication backbone, routing, switching, detection, interconnects and quantum repeaters (devices that can faithfully relay quantum information and extend quantum communication range).

45 Stebila D (2009) The Case for Quantum Key Distribution. In: Sergienko A., Pascazio S., Villoresi P. (eds) Quantum Communication and Quantum Networking. QuantumComm 2009. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, vol 36. Springer, Berlin, Heidelberg. DOI: https://doi.org/10.1007/978-3-642-11731-2_35

46 QuintessenceLabs (2019) QKD Becomes an Essential Part of Quantum Safety. <https://www.quintessencelabs.com/blog/qkd-becomes-essential-part-quantum-safety/>

Australia's opportunity

Australia has developed significant theoretical and experimental expertise in the development of quantum communications technology and was an early leader in the development and commercialisation of quantum technologies for secure communications. Australia's first quantum technology start-up QuintessenceLabs was established by researchers from ANU in 2006 to commercialise quantum-enhanced cybersecurity solutions. Researchers in Australia are seeking to address the challenges of developing free-space (wireless) and wired optical networks for secure communications and networking of quantum devices. Australia also has developed expertise in quantum-safe cryptography development which will be an essential capability to ensure the nation's readiness for the emergence of quantum computing.

If Australia can successfully commercialise technologies that capture 5% of the estimated global market for quantum-enhanced cybersecurity solutions and network technologies by 2040 it could generate $820 million in revenue and 3,300 new direct jobs.

The successful commercialisation and deployment of quantum-enhanced technologies for secure communications can also:

- **support national and industry security** with sovereign capability in secure communication technologies and post-quantum cryptographic methods
- **contribute to global productivity growth** though reduced data loss or compromise through the implementation of secure communications networks.

Case studies

QuintessenceLabs has developed and commercialised quantum-enabled cybersecurity technologies

QuintessenceLabs provides quantum-enhanced cybersecurity solutions. These include full entropy quantum random number generators (QRNG) and crypto-agile key and policy management systems. Unlike most QRNGs based on single photon detections with limited throughput, QuintessenceLabs' QRNG uses quantum tunneling to provide truly random numbers at very high rates for larger-scale security and other applications. QuintessenceLabs is also at the forefront of the development of quantum key distribution (QKD) technology. QuintessenceLabs emerged from research by the ANU's Quantum Optics Group and has received funding from In-Q-Tel, Westpac Group and the Australian Department of Defence.

Australian National University's InSpace Laser Communications Program is developing technology for a quantum communications network

ANU has embarked on research program to develop and demonstrate technology required for optical quantum communications networks. The first stage includes development of a $2.4 million Quantum Optical Ground Station dedicated to space and optical communications research. Future initiatives include the development and demonstration of free-space continuous variable QKD technology in collaboration with the German Aerospace Centre.

3.4 Enabling technologies and services

An emerging quantum technology industry will require high quality enabling technologies and services. Providing enabling instruments, tools and devices as well as education and consulting services to the domestic and global quantum sector will generate strategic benefits and early revenue streams for Australia's quantum industry.

Demand for high quality enabling technologies and services will increase as the global quantum industry develops. While the associated economic opportunity was not quantified for this Roadmap, these enabling services and technologies will be a critical enable of the industry's growth and can also provide a valuable early revenue streams to the sector.

Australia's opportunity

Quantum technology R&D requires specialised instruments and tools. Reliable and cost-effective access to critical equipment and capabilities such as precision optics, custom electronics and cryogenics will become an increasingly important feature of the quantum industry's supply chain. Australia does not have significant capabilities in these areas at present, but there may be valuable opportunities to enter global supply chains. Local companies MOGLabs and Liquid Instruments have both commercialised scientific instruments that address the needs of R&D labs. These companies demonstrate Australia's potential to scale the development and provision of scientific devices, instruments and technologies to service the global quantum technology sector.

Growth in quantum-related advisory and consulting services to governments, defence agencies and large companies is also expected as industry seeks to engage, educate and partner with potential end-users over the next few decades. Providing education, consulting services and enabling instruments could deliver important strategic benefits and early revenue streams to Australia's quantum industry. Australia's quantum experts are well-placed to advise and support governments and businesses to engage with quantum technologies, both nationally and overseas, due to the nation's strong quantum research capabilities and services industry. For example, Australian researchers established h-bar Quantum Technology Consultants to help governments and businesses navigate the next generation of quantum technologies.

Case studies

MOG Laboratories provides high-performance laser technologies for research institutions in quantum physics and technologies

MOGLabs, found in 2007 by The University of Melbourne, develops scientific instruments such tuneable lasers, laser electronics and instrumentation, optical amplifiers, radio frequency (RF) synthesisers and laser wavelength measurement devices. The market for MOGLabs technologies is expected to expand beyond research laboratories as quantum technology applications are demonstrated and commercialised. It has now established sales offices in the United States and Germany.

Liquid Instruments is simplifying workflows for experimental measurement and control with flexible hardware platforms

Liquid Instruments provides equipment and instruments to help professionals, scientists, engineers and students to collect data, perform measurements and control experiments. Liquid Instruments' reconfigurable hardware platform Moku:Lab provides the functionality of twelve instruments on a single device at lower cost, by simplifying workflows that would otherwise require multiple pieces of instrument equipment. Liquid Instruments was founded by a team of experimental physicists and engineers from the Australian National University.

4 Enabling Australia's quantum technology industry

To maintain its competitive advantages in quantum R&D, overcome the associated challenges, and enable the growth of a valuable and impactful industry, Australia must consider how it can:

- **focus** and coordinate its quantum industry development efforts
- build Australia's quantum workforce and infrastructure **capability**
- support productive **collaboration** with local and international partners
- enhance the **readiness** of governments, society and end-users for next generation quantum technologies.

For the quantum technology industry to become commercially successful it will be important to accelerate the demonstration and commercialisation of technologies. However, sustained investment in fundamental and applied research will be critical to position the industry for long-term opportunities.

Preparing Australia to capture the most value from quantum technology development will require leadership and collaboration from all stakeholders in Australia's quantum ecosystem.

Preparing Australia to capture the most value from quantum technology development will require leadership and collaboration from all stakeholders in Australia's quantum ecosystem. To realise a thriving quantum industry for 2040, it is envisioned that Australia's:

- **governments** consider establishing a coordinated strategy to support the growth of the domestic quantum industry; sustaining Australia's quantum research excellence, accelerating demonstration and commercialisation activities, and facilitating collaboration and engagement activities.
- **publicly funded research agencies** (PFRAs) play a critical role in facilitating the translation of quantum technology from the research sector into industry, meeting both civilian and defence needs
- **research** organisations continue to undertake world-class R&D, providing a solid foundation of deep domain expertise and IP that underpins the creation of new technologies and businesses
- **education** providers expand their offerings, including vocational training options that provide the practical skills needed to industrialise quantum technology
- **investors** ride out a hype cycle to see significant long-term returns, and position themselves well for future investment opportunities
- **standards** groups take a lead role in defining global best-practices and increase Australia's competitiveness
- **industry end-users** take part in early demonstration and adoption of quantum technologies, supporting the commercialisation of technologies that enable improved business performance.

The following sections describe recommendations for specific near-term and sustained actions that are designed to support the long-term success of Australia's quantum technology industry. Each action could be commenced immediately, with follow up activities arising as the industry begins to scale.

Summary of recommendations

Realising the benefits associated with the 2040 vision will not occur without coordinated action to enable the growth of Australia's quantum technology industry. The following table provides a high-level overview of near-term actions designed to support the long-term success of Australia's quantum technology industry for consideration by stakeholders in Australia's quantum ecosystem. These activities could be commenced immediately, with follow up activities arising as the industry begins to scale. These actions are described in greater detail in the following sections.

FOCUS

Focus and coordinate Australia's quantum industry development efforts.

CAPABILITY

Build Australia's quantum workforce and infrastructure capabilities.

KEY RECOMMENDATIONS FOR CONSIDERATION

Develop a national quantum technology strategy to implement this roadmap's enabling actions and set long-term strategic priorities, commitments and indicators of success for Australia's quantum industry.

Explore efficient and effective funding mechanisms to support the demonstration and commercialisation of quantum technology applications and enable the growth of emerging quantum businesses.

Attract, train and retain the best quantum talent and assess the future quantum technology workforce's skill needs to inform strategic capability development and growth.

Assess the industry capabilities and infrastructure facilities that will be critical to the success of a domestic quantum industry and develop business cases to address any gaps.

ADDITIONAL RECOMMENDATIONS

- Support entrepreneurship and accelerator programs that enhance the commercialisation skills of deep technology start-ups.
- Continue to support and leverage Australia's shared research infrastructure through the National Collaborative Research Infrastructure Strategy to promote open collaboration and cost-effective capital expenditure.
- Enhance research and training linkages between Australian Universities with complementary quantum strengths.
- Proactively explore and address any unknown ethical, social or environmental risks that may arise with the next generation of quantum technologies.

COLLABORATION

Support productive collaboration with local and international partners.

Establish multidisciplinary and multi-institution projects to demonstrate commercial applications of advanced quantum technologies; and develop software applications and control techniques for noisy intermediate-scale and large-scale quantum computers.

Promote Australia's domestic quantum technology capabilities and explore opportunities to undertake R&D projects with trusted partners.

- Undertake a thorough assessment of critical materials and components for quantum technologies.
- Develop strong guidance and standards for the development and deployment of quantum applications.

READINESS

Enhance the readiness of governments, society and end-users for next generation quantum technologies.

Provide clarity on the implementation of defence trade control regulations to provide confidence to the industry and ensure that Australia's IP and national security are protected.

Encourage proactive local end-user and government engagement with Australia's quantum ecosystem.

- Consider encouraging universities to ensure that their IP management practices encourage collaboration, entrepreneurship and commercialisation.
- Enhance domestic capabilities and engage with international efforts to develop post-quantum cryptographic methods.

4.1 Focus

Focus and coordinate Australia's quantum industry development efforts by implementing a national strategy to enhance its quantum technology R&D strengths and accelerate the demonstration of viable quantum technology applications through targeted investments.

	Recommendations	Lead	Support
1.1	Consider establishing a taskforce to develop a national quantum technology strategy to implement this Roadmap's enabling actions and set long-term strategic priorities, commitments and indicators of success for Australia's quantum industry. Participation from both federal and state governments, and consultation with the quantum industry, research institutions, and end-users will be critical.	Governments, Industry, Research, End-users	All
1.2	Explore efficient and effective funding and investment mechanisms to support the demonstration and commercialisation of quantum technology applications beyond the remit of ARC funding and enable the growth of emerging quantum businesses. Key considerations include leveraging private investment, incentivising end-user engagement, and enabling access to finance options for quantum technologies that demonstrate commercial potential.	Governments, Investors	All

4.2 Capability

Undertake a thorough assessment of the industry capabilities that will be critical to an Australian quantum industry to inform and enable investment in the talent and infrastructure required to research, develop, engineer, fabricate and commercialise quantum technology applications.

	Recommendations	Lead	Support
2.1	Assess the future quantum technology workforce's skill needs to inform strategic capability development and growth. Engaging with research organisations, quantum technology start-ups and early end-users will be critical to this assessment.	Education	All
2.2	Enhance Australia's ability to attract, train and retain the best quantum talent. Key actions include: • Engage in targeted marketing and recruitment to develop a critical mass of quantum talent • Explore visa and migration policies that support the attraction and retention of top global talent in quantum-related physics, computer science, and engineering Consider expanding reference to quantum physics and modern quantum technology in the Australian high school physics curriculum to increase public awareness of quantum technology and support long-term workforce development.	Governments, Education, Research, Industry	All
2.3	Assess the broader industry capabilities that will be critical to the success of a domestic quantum industry and address gaps in Australia's capabilities. Relevant capabilities include quantum device design, engineering and fabrication, precision electronics, optics, software development, materials, manufacturing, and metrology.	Governments	All
2.4	Develop and evaluate business cases for the establishment of infrastructure facilities to address gaps identified in Australia's domestic industry. This may include: • Supporting infrastructure (such as flexible fabrication facilities) that can service a broader range of industries • National quantum technology facilities to enable access to and engagement with quantum hardware (e.g. state-of-the-art quantum computing hardware).	Research, PFRAs, Industry	All
2.5	Explore ways to support entrepreneurship and accelerator programs that enhance the commercialisation skills of deep technology start-ups.	Governments	Industry, Research
2.6	Explore opportunities to leverage the National Collaborative Research Infrastructure Strategy to promote collaboration and cost-effective capital expenditures.	Research, Governments	All

4.3 Collaboration

Support productive collaborations with local and international stakeholders in the quantum industry to develop quantum technology solutions. Engagement with end-users to scope and demonstrate commercial applications will be critical.

	Recommendations	Lead	Support
3.1	Establish multidisciplinary and multi-institution projects to demonstrate emerging commercial applications of advanced quantum technologies in collaboration with end-users.	Research, End-users	Governments, Industry, End-users
3.2	Establish a multidisciplinary and multi-institution research initiative focused on the development and evaluation of software applications and quantum control techniques for noisy intermediate-scale and large-scale quantum computers. This could be supported by the establishment of a quantum technology facility that enable access to a variety of emerging quantum computing systems (see Action 2.3).	Research	Governments, Industry, End-users
3.3	Promote Australia's domestic quantum technology capabilities and strengths through trade missions and science diplomacy, with a focus on inward bound delegations.	Research, Industry	Governments
3.4	Explore opportunities to undertake research and demonstration projects with trusted international partners. Priority partners include Australia's Five Eyes Alliance allies (Canada, New Zealand, the United Kingdom, and the United States), NATO member countries, and other countries conducting major quantum research programs.	Research, Industry	All
3.5	Enhance research and training linkages between Australian universities with complementary quantum strengths.	Education, Research	Governments

4.4 Readiness

Position Australian government and businesses for next generation quantum technologies through education and communication campaigns, fit-for-purpose intellectual property practices and controls, and effective transition planning.

	Recommendations	Lead	Support
4.1	Provide clarity on the implementation of defence trade control regulations and maintain a dialogue between stakeholders to provide confidence to the industry and ensure that Australia's IP and security is protected.	Defence, Governments	Research, PFRAs, Industry
4.2	Explore ways to enhance proactive engagement between local end-users, governments, and Australia's quantum sector.	Governments, End-users, Research, Industry	All
4.3	Proactively explore and address any unknown ethical, social or environmental risks that may arise with the next generation of quantum technologies: • Embed responsible innovation practices into quantum technology R&D • Foster dialogue with international governments and partners to understand practical policy responses to any emerging risks.	Research, PFRAs, Industry, Governments	All
4.4	Undertake a thorough assessment of critical materials and components for quantum technologies and investigate Australia's potential to enter these supply chains.	Research, PFRAs, Industry	All
4.5	Develop strong guidance and standards for the development and deployment of quantum applications in collaboration with international standards bodies to support quality assurance and interoperability.	Standards bodies, PFRAs	All
4.6	Consider encouraging the research sector to ensure that their IP management practices encourage collaboration, entrepreneurship and commercialisation	Governments	All
4.7	Enhance domestic capabilities and engage with international efforts to develop post-quantum cryptographic methods.	PFRAs, Research, Industry	Research

5 Implementation considerations

Applications of quantum technologies are beginning to emerge from the laboratory and their successful commercialisation has the potential to create a new multi-billion-dollar industry generating thousands of jobs for Australia. However, the rest of the world is rapidly accelerating its investments into quantum technology. If Australia wants to remain world-class in this field, it must act now.

Implementing the enabling actions described in this Roadmap will be essential to supporting the long-term success of Australia's quantum technology industry but these actions are not exhaustive. Developing an industry growth strategy for Australia's quantum technology sector that remains agile and responsive to new developments is critical. Issues that will require ongoing consideration as the industry evolves include:

- How can Australia balance supporting a range of early stage quantum technologies with pursuing major opportunities that will require a critical mass of investment?
- What is the appropriate balance between basic and applied research to position Australia for long-term opportunities as well as near-term wins?
- How can public investment in quantum technology support industry development while also encouraging growth in private investment from venture capital and end-user organisations as commercial applications become more readily available?
- How can Australia support the movement of people and ideas between industry and academia?
- Which applications of quantum technology can tackle Australia and the world's greatest challenges?

In developing this Roadmap, CSIRO brought together diverse stakeholders from the quantum ecosystem, including universities, other research organisations, PFRAs, start-ups, state and federal governments, multi-national businesses and SMEs to discuss the future of this exciting industry. This approach reflects the importance of the collaborative effort that will be needed to refine and operationalise the Roadmap's recommendations and enable the growth of Australia's quantum technology industry. CSIRO stands ready to support Australia's quantum ecosystem to pursue these opportunities and realise the significant opportunities that quantum technology presents.

Appendices

A Economic assessment methodology

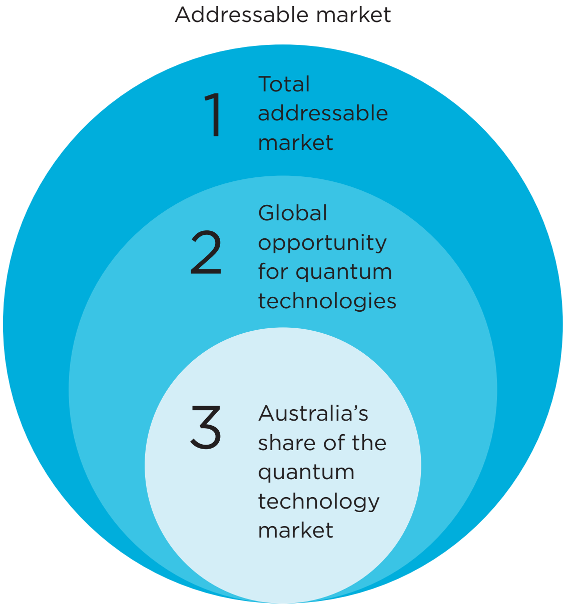
Economic analysis was undertaken to assess the commercial opportunity in quantum technology for Australia by 2040. This section summarises the results, methodology and parameters, developed in consultation used to produce the estimates presented in this Roadmap.

Summary of results

The market sizing estimates used throughout the reported are summarised here. Discrepancies in summations are attributed to differences in rounding.

	Computing	Sensing	Comms	Total
(1) Addressable market by 2040 – global annual revenue $B AUD	1,262	624	816	2,702
(2) Global quantum opportunity by 2040 – annual revenue $B AUD	50	19	16	86
(3) Australia's quantum opportunity by 2040 – annual revenue $B AUD	2.5	0.9	0.8	4.3
(4) Direct employment creation by 2040 ('000 employees)	10	3	3	16

Methodology



1. Total addressable market by 2040 = $A \times (1+B)^{20}$
2. Global opportunity for quantum technologies by 2040 = $A \times (1+B)^{20} \times C$
3. Australia's share of the quantum technology market by 2040 = $A \times (1+B)^{20} \times C \times D$
4. Potential job creation for Australia by 2040 = $(A \times (1+B)^{20} \times C \times D) / E$

	Parameters	Computing	Sensing	Comms
A	2020 estimate of addressable market ($B AUD)	393	195	254
B	Forecast real annual growth in the addressable market (CAGR)	6%	6%	6%
C	Market share for quantum technologies by 2040	4%	3%	2%
D	Market share of quantum-technologies captured by Australia by 2040	5%	5%	5%
E	Average industry revenue to employment ratio ($'000 per employee)	255	325	244

A. 2020 estimate of the addressable market

The addressable market for advanced computing, sensors and secure communications was estimated to help understand the potential scale of opportunities for quantum technologies over the next few decades.

- **Computing**: The advanced computing market in 2020 is estimated at $268 billion USD,[47] or $393 billion AUD at an exchange rate of 1.47 AUD per USD.[48] This estimate is based on BCC Research and covers revenue from advanced computation, analytics and simulation related software, services and systems. It includes revenue across the technology stack (e.g. programming languages, graphical user interfaces, compilers, middleware, components, deployment, analysis and advisory) for applications in analytics, simulation, optimisation, machine learning, statistical analysis and data mining, as well as edge and distributed computing-related operations.[49]
- **Sensing**: The addressable sensing market in 2020 is estimated at $132 billion USD,[50] or $195 billion AUD. This estimate is based on BCC Research and describes business and government spending in advanced sensing across domains in image, biosensors, chemical, RADAR, position, flow, level, wireless and fibre optic; and across major end-user types such as medical technologies, mining equipment, environmental monitoring and avionics.
- **Communications**: Global cyber security and secure communications spending in 2020 is estimated at $173 billion USD,[51] or $254 billion AUD. This estimate is based on AustCyber research and describes expenditure across the cyber security stack, and underlying processes in software (e.g. encryption and authentication solutions), hardware (e.g. equipment manufacturing) and services (e.g. assessment, integration and testing) for end-users in industries such as banking, telecommunications, defence, healthcare and government.

B. Forecast real annual growth in the addressable market

Global demand for applications in computing, sensing and secure communications are expected to increase. This is due to expected widening industry adoption, incremental technical improvements, and spending on new innovations over the next two decades. Several sources for example estimate demand for advanced computing and analytics to grow from between 3% and 10% per annum over the coming decade.[52] Similarly, analysis from BCC Research estimates the sensing market to grow at approximately 10% per annum over the next 5 years in real terms.[53] Several sources have also estimated demand for secure communications and cyber security to grow at about 10% per annum in real terms over the next 5–10 years.[54] In the long-term, global demand for computing, sensing and secure communications are expected to converge towards long-run real GDP growth of advanced economies. This is currently estimated at around 1.6% per annum.[55] For this reason, the scenario for 2020–2040 addressable market growth was selected at 6% per annum.[56]

47 BCC Research LLC (2019). Analytics Markets: A Global Outlook; BCC Research LLC (2018). Global Markets and Technologies for Edge Computing Through 2023.

48 Morningstar (2019). Currency Data - USD to AUD as at 03/12/2019.

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50 BCC Research LLC (2017). Sensors Markets: A Global Outlook.

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52 BCC Research LLC (2019). Analytics Markets: A Global Outlook; BCC Research (2019). Global Cloud Computing Technologies; Technavio (2018). Global Simulation and Analysis Software; Technavio (2018). Global High-Performance Computing Market.

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55 IMF (2019). Real GDP Growth – Annual Percent Change, Advanced Economies. <https://www.imf.org/external/datamapper/NGDP_RPCH@WEO/OEMDC/ADVEC/WEOWORLD>

56 The COVID-19 pandemic will have significant short run economic impacts, including a likely recession, however CSIRO expects the long run impacts to be small, and for economic growth rates to return to the levels projected well before 2040.

C. Market share captured by quantum technologies by 2040

This analysis assumes a scenario where quantum technologies can account for 2–4% of the addressable market by 2040. It is acknowledged that there is high technical and economic uncertainty surrounding the long-term development and adoption of quantum technologies. It is possible that quantum technologies may fail to capture a significant share of these markets by 2040. However, it is also possible that this assumption is far exceeded. Furthermore, commercial revenue does not reflect the total economic and social value creation from quantum technologies. Examples include benefits to national security and productivity gains for corresponding verticals.

D. Market share of quantum-computing captured by Australia by 2040

This scenario assumes that Australia can capture about 5% of the quantum technology market by 2040. Australia accounts for around 5% of annual global investment into non-classified quantum-technology research, and about 4% of the quantum-technology research workforce.[57] To realise (or even exceed) this market share Australia must maintain its research strength and expands its industry activity through effective planning, and targeted investment.

E. Industry revenue to employment ratio

Revenue to employment ratios in comparable industries are used to approximate potential job creation from the development of a local quantum industry. The industry revenue-to-employment ratio for quantum:

- *Computing* is assumed at $255,000 per employee based on the average ratio of companies with operations in Australia in computer systems design, systems integration, software simulation and related hardware and software services between 2010 and 2019 (inflation adjusted).[58]
- *Sensing* is assumed at $325,000 per employee, based on the average ratio of businesses in Australia in navigational, measuring and scientific equipment development and manufacturing between 2010 and 2019 (inflation adjusted).[59]
- *Communications* is assumed at $244,000 per employee, based the average spending to employment ratio in Australian cyber security today.[60]

While these assumptions give an indication of potential workforce scale by 2040, realised employment levels will vary with demand for Australian quantum technologies and the business models selected by industry.
The estimates do not account for broader indirect job creation in flow-on.

57 Ministry of Economic Affairs Netherlands (2015). Global Developments Quantum Technologies. <https://connect.innovateuk.org/documents/11487824/26842605/Global+Developments+in+Quantum+Technology/>;
Government Office for Science UK (2016). The Quantum Age: Technological Opportunities. <https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/564946/gs-16-18-quantum-technologies-report.pdf>

58 IBISWorld (2019). Australian Industry (ANZSIC) Report M7000. Computer System Design Services in Australia.

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B Australia's quantum landscape

This appendix provides a high-level overview of some of the key research and industry players in Australia's quantum technology landscape.

Table 2. Quantum Physics Excellence in Research for Australia (ERA) ratings and related companies for university

University	Quantum Physics ERA rating[61]	Related companies
Australian National University	5	• QuintessenceLabs • Liquid Instruments • Nomad Atomics • Quantum Brilliance
Curtin University	4	
Griffith University	5	
Macquarie University	4	• Lucigem • Redback Systems
Monash University	5	
RMIT University	5	• h-bar
Swinburne University of Technology	4	
The University of Sydney	5	• Q-CTRL • Microsoft
University of Adelaide	Not Assessed	• CryoClock
University of Melbourne	5	• MOGlabs • IBM
University of New South Wales	5	• Silicon Quantum Computing
University of Queensland	5	
University of Technology Sydney	5	• h-bar
University of Western Australia	5	

ERA ratings: 5 - Well above world standard; 4 - Above world standard.

61 Australian Research Council (2019) State of Australian University Research 2018-19. Australian Government.

Table 3. CSIRO and CoE quantum-related research

Organisation	Focus	Members
ARC CoE for Quantum Computation and Communication Technology (CQC2T)	• Optical quantum computation • Silicon quantum computation • Quantum communications • Quantum information processing • Architecture and algorithms • Scale-up engineering • Optical quantum computation • Silicon quantum computation • Quantum communications • Quantum information processing • Architecture and algorithms • Scale-up engineering	• University of New South Wales (lead) • University of Melbourne • ANU • Griffith University • UQ • RMIT University • UTS
ARC CoE for Engineered Quantum Systems (EQUS)	• Quantum materials • Quantum diagnostics and imaging • Quantum engines and instruments	• UQ (lead) • UWA • The University of Sydney • Macquarie University • ANU
ARC CoE in Future Low-Energy Electronics Technologies (FLEET)	• Topological materials • Exciton superfluids • Light-transformed materials • Atomically thin materials • Nanodevice fabrication	• Monash University (lead) • UNSW • ANU • RMIT University • Swinburne • UQ • University of Wollongong
ARC CoE in Exciton Science	• Quantum and classical mechanical exciton theory and modelling • Spectroscopy • Design and fabrication of materials and devices for applications in solar, lighting and security, and exciton control	• University of Melbourne (lead) • Monash University • RMIT University • UNSW • The University of Sydney

Organisation	Focus	Members
ARC CoE for Gravitational Wave Discovery (OzGrav)	• Quantum squeezing in gravity-wave astronomy • Instrumentation for Advanced LIGO, the Square Kilometre Array and the next generation of gravitational wave detectors • Gravitational wave data collection from black holes and neutron stars • Using gravitational wave detection to inform astrophysical exploration	• Swinburne University • Australian National University • Monash University • The University of Adelaide • The University of Melbourne • The University of Western Australia
ARC CoE for Nanoscale BioPhotonics	• Advanced light-based sensing tools • Improved imaging of the living body and other dynamic biological systems • Enabling discovery of chemical, nanomaterial and fibre-based light responsive tools	• The University of Adelaide • Macquarie University • RMIT University • Griffith University • UNSW
CSIRO	• Superconducting Quantum Interference Devices • Quantum software and system security • Quantum-safe cryptography • Quantum-safe protocols • Quantum communications and randomness • Quantum algorithms	

Table 4. Overview of Australian industry activity

Company	Technology	Associated Universities	Investment
Archer	Quantum computer chip designed to operate at room temperature.	• University of Sydney	• ASX-listed • Received $15,000 from the NSW government in 2019 to support the use of the University of Sydney's prototyping facilities
CryoClock	Cryogenic sapphire oscillator technology for ultra-precise timing	• IPAS • University of Adelaide	
h-bar consultants	Quantum technology consultants	• RMIT University • UTS	
IBM (US)	Full stack quantum computing (superconducting qubits)	• University of Melbourne (IBM Q Network Hub)	
Liquid Instruments	Reconfigurable hardware for experimental measurement and control	• ANU	• $11M Series A funding in January 2019
Lucigem	Fluorescent nano-diamonds for applications in quantum engineering, life and medical sciences and biomedicine	• Macquarie University • University of Sydney	
Max Kelsen	Artificial intelligence and quantum computing consulting	• UQ	
Microsoft (US)	Full stack quantum computing	• University of Sydney (Station Q Sydney Laboratory)	
MOGLabs	High-performance laser technologies for research institutions	• University of Melbourne	
Nomad Atomics	Quantum cold-atom sensors for gravimetry and accelerometry	• ANU	
Q-CTRL	Quantum control solutions for reduced decoherence and errors	• University of Sydney	• $22M in Series A VC funding in September 2019
Quantum Brilliance	Diamond-based quantum computing technology	• ANU	• $0.6M in pre-seed technology translation funding
QuintessenceLabs	Quantum cyber security products, encryption, and random number generation	• ANU • UQ • CQC2T	• $2M in seed funding in 2008 • Undisclosed investment by In-Q-Tel in 2020
Redback Systems	Compact spectrograph for high resolution broad-spectrum imaging	• Macquarie University	
Rigetti Computing (US, previously QxBranch)	Rigetti Computing's Australia presence is focused on quantum computing applications development		• Rigetti acquired QxBranch in July 2019
Silicon Quantum Computing Pty Ltd	Silicon-based quantum computing technology	• CQC2T	• Formed for $83M as a joint venture between Telstra, CBA, UNSW and the NSW and Australian Governments in 2017

C Public funding for quantum technology

Commenced and committed government investments since 2018[62]

Country/union	Government funding commencing from 2017 onwards (AUD, millions)
Australia[63,64,65]	90
Canada[66,67]	22
European Union[68,69]	1,637
Germany[70,71]	1,036
India[72]	1,646
Japan[73]	294
Netherlands[74,75]	670
Russia[76]	1,161
South Korea[77]	59
Switzerland[78]	51
United Kingdom[79,80,81]	1,074
United States[82,83]	1,874

62 At an exchange rate of 1.47 AUD per USD. Morningstar (2019). Currency Data - USD to AUD as at 03/12/2019.

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71 Quantum Flagship (2018) German government allocates 650 million euros for quantum technologies. Viewed 27 February 2020, <https://qt.eu/newsroom/german-government-allocates-650-million-euros-for-quantum-technologies/>

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74 Quantum Delta NL (2019) National agenda for quantum technology <https://qutech.nl/wp-content/uploads/2019/09/NAQT-2019-EN.pdf>

75 Netherlands Foreign Investment Agency (2019) Quantum technology: The Netherlands. Viewed 27 February 2020, <https://investinholland.com/wp-content/uploads/2019/11/NFIA_Quantum_Brochure_2019.pdf>

76 Schiermeier Q (2019) Russia joins race to make quantum dreams a reality. Nature (news). Viewed 27 February 2020, <https://www.nature.com/articles/d41586-019-03855-z>

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Photos

p. vi Internal infrastructure of dilution refrigerator used to create a cryogenic operating environment for quantum systems. Credit: Nick Bowers for Silicon Quantum Computing

p. 4 Trapped-ion quantum computer at the University of Sydney, built by Q-CTRL founder Prof. M. J. Biercuk. Credit: M. J. Biercuk

p. 9 Kai Wang holding a sample that has multiple nanostructured metasurface lenses designed for quantum light imaging at the Nonlinear Physics Centre, Research School of Physics, Australian National University. Credit: Lannon Harley, ANU

p. 11 Ms Jeina Lazar using the Lindfield Clean Room. Credit: CSIRO

p. 14 A trapped ion quantum computing chip. Credit: Y. Colombe/National Institute of Standards and Technology

p. 16 Inside the EQUS Bose Einstein Condensate laboratory. Credit: Patrick Self

p. 18 PhD student Georgina Carson working on the atomic engineering of qubits in silicon at Silicon Quantum Computing. Credit: CQC2T

p. 23 SQUIDs technology, part of a 2D step-edge Josephson junction array device. Credit: CSIRO

p. 27 The Australian National Fabrication Facility Research and Prototype Foundry cleanroom at the University of Sydney. Credit: University of Sydney

p. 28 Cleanroom in the Sydney Nanoscience Hub at the University of Sydney. Credit: University of Sydney

p. 36 Developing a single photon source. Credit: Patrick Self and EQUS

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