Australian Government

2021

National Research Infrastructure Roadmap

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Ministers' Foreword

NRI Roadmap matches Aussie smarts with future national infrastructure needs

In a rapidly evolving and competitive global economy, Australia's prosperity relies on the excellence of our research and innovation sector.

Millions of people around the world rely on technologies and products made possible by Australian research. These technologies are developed and commercialised through our cutting-edge universities and research agencies, supported by our national research infrastructure.

Every five years, the Government renews its approach to national research infrastructure through a strategic Roadmap to ensure such infrastructure remains relevant and responsive to Australia's needs, and those of our world-class research sector.

The Roadmap helps Australia to maintain research excellence, increase innovation, address emerging challenges and deliver step-changes to improve our nation's standard of living, strengthen its economic standing and build sovereign capabilities.

The 2021 National Research Infrastructure Roadmap sets out Australia's research infrastructure capability and areas of importance for the next 10 years. The Roadmap considers the current research context here and internationally, including lessons learned through the 2019–20 bushfires and the COVID-19 pandemic.

Research excellence requires a systemic, whole-of-government approach. The Morrison Government's Modern Manufacturing Strategy has set out clear priorities and leverages our strengths and resources to build new sources of growth. Aligning the Roadmap to these priorities means we can focus on supporting sectors where Australia can build scale and produce impactful outcomes.

The Roadmap supports and leverages other Government strategies, including:

- the Digital Economy Strategy, which lays the foundation for Australia to be a leading digital economy by 2030;
- the Action Plan for Critical Technologies, which is working to protect and promote critical technologies in Australia's national interest; and
- the National Climate Resilience and Adaptation Strategy, which is positioning Australia to better anticipate, manage and adapt to our changing climate.

Investment in our National Research Infrastructure must also consider Australia's economic prosperity, social cohesion and national security.

The Roadmap also builds on the University Research Commercialisation Scheme, which lays out a comprehensive set of reforms to boost cooperation between universities and industry, and to drive commercial returns.

The focus of the Roadmap is on research infrastructure that will deliver long-term national benefit and support strategic international partnerships.

The Roadmap also supports and encourages greater translation and commercialisation of research by allowing industry and other research end-users to engage more effectively.

We thank all the stakeholders who engaged in the consultation process for this Roadmap. Your expertise and knowledge have been invaluable and will ensure Australia's investment in research infrastructure is applied to best effect.

The development of the 2021 National Research Infrastructure Roadmap was informed by the excellent work of the Roadmap Expert Working Group, led by Dr Ziggy Switkowski.

We extend our thanks to this expert group, which represents a wealth of experience and expertise from research, business and technology sectors.

The Hon Stuart Robert MP, Acting Minister for Education and Youth

The Hon Melissa Price MP, Minister for Science and Technology

Chair's Foreword

Long term investment in Australia's research infrastructure has produced a strong, stable and adaptable system that allowed Australian research and industry to pivot to do what was needed to help.

In coming decades, Australia will face significant change and we may need to respond as quickly as we have done recently. Future technological progress will be driven by working across disciplines, collaborating across institutions and accessing state of the art distributed facilities managed by a highly skilled workforce.

Moreover, in addition to the steady accumulation of knowledge, the national interest will define practical priorities. Government support will also encourage advanced planning for the commercialisation of research.

This Roadmap does not prescribe what should, and should not, be invested in to navigate these changes. That happens through the next step: the Research Infrastructure Investment Plan.

However, we have made suggestions for step-change investments that we believe will make a tangible difference to researchers and industry in Australia in future years.

As someone who has worked closely with technology in both academic and commercial settings, I know how difficult it is to predict the future beyond five years – especially when you are trying to future-proof for decades. Ensuring there is enough flexibility to take advantage of new technologies as they emerge is important.

Enabled by the digital revolution, this current period in history is associated with faster and greater transitions than ever before. This will necessitate a transition of the Australian research sector and its supporting research infrastructure. To ensure that Australia can respond to emerging opportunities (and importantly, gain best value for money for the investment in research infrastructure) expert advice and continuity between Roadmaps is required. We have made recommendations for how that might best be achieved.

Over the course of my career, I have been fortunate to work with many innovative people and companies. I have worked with companies who invested in their people, companies who were building a future Australia and companies whose products and services were so good they made you get up in the morning, anxious to contribute. The national research infrastructure community reminds me very much of those organisations and I thank all those stakeholders for engaging in the process, difficult as it was in a COVID-constrained environment.

National research infrastructure is making a real difference to Australian researchers, industry and government and is well positioned to do that for the future. The passion, enthusiasm and extraordinary knowledge of stakeholders was reflected in the input to this Roadmap.

I would like to express my thanks to the members of the diligent and insightful Expert Working Group that it was my privilege to lead, and the Taskforce that supported us.

I look forward to seeing the developments from this Roadmap and the difference it makes to our nation in coming years and decades.

Dr Ziggy Switkowski AO

A CTD-rosette is recovered from Antarctic waters by CSIRO research vessel *Investigator*. Image credit: CSIRO/Merinda McMahon

Contents

Executive summary

National research infrastructure (NRI) comprises a range of nationally significant assets, facilities and services that support leading-edge research and innovation. It is more than instruments and devices: a highly skilled workforce supports both the equipment and the researchers that use it. Australia's NRI network has been built over decades and successfully underpins fundamental and applied research across many disciplines.

As the global pandemic continues and Australia transitions towards net zero emissions, the role of science in addressing our biggest domestic and global challenges is significant. Investing in NRI to catalyse and accelerate the research needed to address these challenges has never been more important.

The 2021 National Research Infrastructure Roadmap (Roadmap) details a clear path for Australia to build on strong existing NRI foundations and deliver step-change capability to support future research needs. The objective of these NRI investments is to ensure Australian research remains competitive internationally, protect unique national assets, manage sovereign risk, support social cohesion and stimulate the creation of new industries.

The Expert Working Group has found that the following must be considered when planning for the infrastructure needs of the research and innovation community:

- Support for fundamental research is critical. The right NRI investment ensures that Australia can undertake world-class research in areas of significance.
- Australia's NRI investment is strong and contributes to the efficiency and effectiveness of our research effort. In times of uncertainty, NRI is especially important.
- There is opportunity for Australia to make key investments in NRI, to deliver step-change in research outcomes that can improve our standard of living, strengthen our economy and build sovereign capabilities to protect Australia's interests.
- NRI needs to engage more effectively with industry and other research end users. This will increase the impact of NRI investment and lead to greater translation of research.

Finding 1:

The current NRI portfolio positions Australia well in its research effort and is expected to continue to do so:

- A robust funding model with ongoing investment to support existing capabilities should remain a key priority for governments.
- The current NRI portfolio provides an essential base to support government priorities, such as the *Modern Manufacturing Strategy*, the *Science and Research Priorities*, the *National Climate Resilience and Adaptation Strategy*, the *Blueprint for Critical Technologies, Australia's Long-Term Emissions Reduction Plan* and the *University Research Commercialisation Scheme*. The quality of the projects and their ability to support a broad range of research should constantly adapt to ensure ongoing relevance to emerging priorities.

Finding 2:

The NRI Principles set as part of the 2016 NRI Roadmap have driven sound investment decisions over the last five years. There is a need to update the Principles to reflect the current context and ensure they continue to meet the evolving needs of modern research.

Finding 3:

Australia's investment in NRI leverages a collaborative approach to maximise the impact of these assets. Co-investment brings a diversity of perspectives, increases creativity and capacity across the system and helps deliver return on investment. Infrastructure investment provides foundations for an ecosystem of expertise, facilities and services to support researchers. The human capital required to operate the NRI is as important in achieving research outcomes as the assets and facilities.

Finding 4:

Exponential growth in data across all disciplines will be a critical challenge for NRI over coming years, highlighting the need for integration of computing and data infrastructure and the maintenance of a strong digital infrastructure ecosystem.

Finding 5:

Researchers are increasingly focused on investigating solutions to complex problems that are not easily solved by a single discipline. Some of the research with the greatest impact is derived from collaboration across the science, technology, engineering and maths and humanities, arts and social sciences disciplines. Outcomes from research in the creative arts, humanities and social sciences disciplines are critical to achieve the economic, social and environmental benefits we strive for. They also play an important role in ensuring social acceptance and uptake of research outcomes, adoption of new technologies and ensuring ethical and responsible development and application of emerging technologies. NRI investment must support all fields of research and encourage their interconnectedness.

Finding 6:

Many NRI facilities are expanding their focus to better cater for the needs of end users, such as conducting regular user satisfaction and needs surveys to help inform operational improvements and future planning to deliver accessible and valuable services. These developments should be further emphasised as measures for focus through future Research Infrastructure Investment Plans.

Finding 7:

The global pandemic has focused the world on science and what it can achieve for humanity. Investing in the next generation of technologies, networks and services will place Australia at the cutting edge of research over the next decade and develop greater levels of sovereign capability.

Recommendations

Recommendation 1: Adopt the NRI Principles

The Principles presented in this Roadmap outline the objectives for NRI investment. The 2021 Principles have been developed in recognition of rapid changes in the research and technology landscape. They are designed to assist decision-making that will advance Australia's interests and build capacity where there is a need to strengthen sovereign capability. Specific Investment Principles have been developed to align opportunities for planning and co-investment with research and industry partners, as well as state and territory governments. The Principles should be adopted by government and implemented in the 2022 Research Infrastructure Investment Plan.

Recommendation 2: Provide continuity and long-term funding to NRI

Australia's current network of national research infrastructure has been extremely successful in supporting national priorities and international collaboration. Funding stability since 2017–18 has resulted in the development of a strong suite of NRI underpinned by a highly skilled workforce. This stability needs to be maintained in recognition of the long-term operations of NRI. Government should maintain or increase current funding levels for NRI beyond 2028–29.

Recommendation 3: Adopt a challenge framework to support NRI planning and investment

The 2021 Roadmap identified key challenges that have significant impact for Australia and around the world. Using a challenge framework to support NRI planning and investment will help address the big issues facing Australia. The challenges below aim to focus research efforts and attract co-investment in the necessary research infrastructure to increase Australia's economic prosperity and improve the lives of individuals:

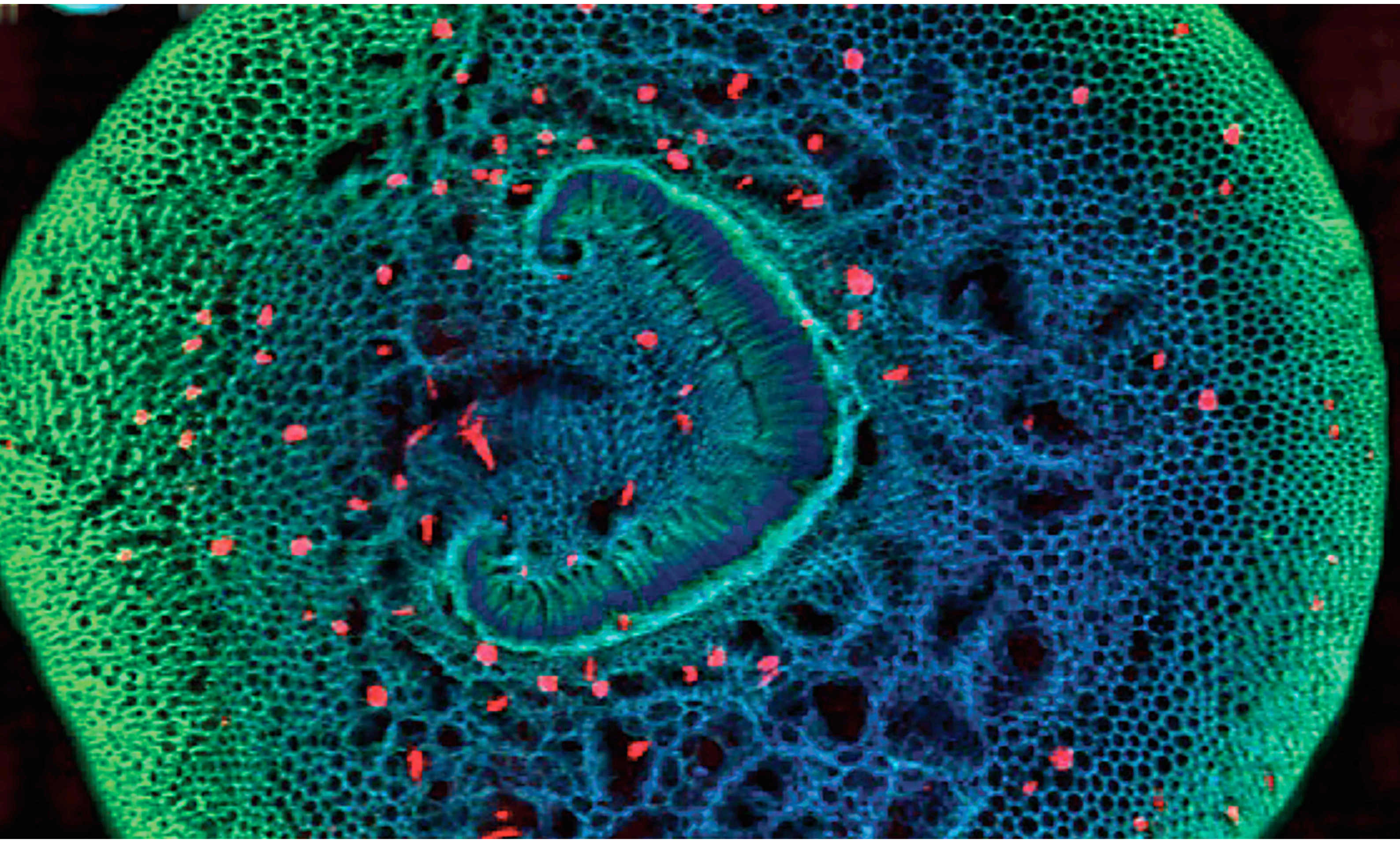
- *Resources Technology and Critical Minerals Processing* – We are a global resources leader stemming from our rich natural resource endowments, huge investments in R&D, proximity to the growing Asian market and a skilled workforce. We can leverage these strengths in combination with our vast critical minerals endowments to deliver critical enablers for a range of sectors.
- *Food and Beverage* – Our success is underpinned by our international reputation for premium, safe and high-quality food and beverage products, strong production capabilities, research expertise and market proximity.
- *Medical Products* – We have strong medical research capability, a reputation for quality and standards and proximity to emerging markets in Asia with rapidly aging demographics and a growing middle class.
- *Recycling and Clean Energy* – We have strong circular economy research capabilities, as well as world-class solar and wind resources and a well-established minerals industry and skills base. We also have a large land mass to build on and experience in delivering large energy projects.
- *Defence* – Defence exports are growing, with a focus on increasing the international competitiveness and success of Australian defence industry. The sector provides advanced technology with cross-sectoral applications and delivers on our national security imperatives as outlined in the Defence Industrial Capability Plan.
- *Space* – Space technologies enable activity across the economy. Our emerging global position is underpinned by research expertise, geographical location, cutting-edge facilities and advanced manufacturing capabilities.
- *Environment and Climate* – Our future prosperity will be safeguarded by positioning Australia to better anticipate, manage and adapt to our changing climate.
- *Frontier Technologies and Modern Manufacturing* – Developing and translating critical technologies required to support modern manufacturing and secure supply chains. Success will include investment in research and commercialisation of critical technologies.

Recommendation 4: Establish an Expert NRI Advisory Group to drive a more effective NRI ecosystem

Government needs ongoing independent, long-term strategic advice on NRI priorities, trends and opportunities. This is best achieved through the establishment of an expert advisory group with a relevant range of skills. This should be established within the next six months.

The immediate priorities for the Expert NRI Advisory Group will be:

- development of a NRI Workforce Strategy to support career pathways, address technical skills shortages and identify capability gaps. NRI is underpinned by a highly skilled and increasingly specialised workforce that needs job security and opportunities for career mobility and professional development.
- a review of current NRI facilities and services to identify opportunities for greater integration and alignment of functions across the network. This should include an assessment of impact to inform the investment levels required in each NRI facility, their levels of maturity and identify areas of consolidation. It should examine current business models to ensure NRI is continuing to meet the needs of users and deliver the most impact.
- providing advice to government on immediate and long-term NRI planning and funding strategies. This includes guidance on the most effective way to support government research priorities and maximise NRI co-investment opportunities. Advice should take into account all research income (Australian and state and territory governments, industry and the research sector) and where the most impact can be delivered.



The Heavy Ion Accelerator enables high-resolution mapping of elemental distributions in plants that soak up metals from the environment. These plants have applications in mining and environmental remediation. Image Credit: University of Melbourne and CSIRO Mineral Exploration, Clayton

Recommendation 5: Drive a more integrated NRI ecosystem

Modern research occurs across disciplinary boundaries to address increasingly complex problems. This requires linkages, interactions and collaboration within and across the NRI system. The future vision of a seamless ecosystem of NRI services for researchers will require an even greater level of collaboration. Considering the NRI ecosystem as a set of functions (outlined below) could draw out opportunities for further collaboration and integration of services:

- observation and monitoring
- computing and modelling
- management of datasets and collections
- fabrication and manufacturing
- measurement and characterisation.

Recommendation 6: Improve industry engagement with NRI

Although improving, there are barriers limiting effective engagement and research translation between NRI and industry. NRI needs to be more visible and accessible to industry and the mutual benefits from closer collaboration should be further promoted. Successful research translation will require a range of elements working together in harmony across jurisdictions. This includes the legal, governance, business and social licence frameworks needed to achieve real impact. The business models around NRI management need to adapt to enable greater research impact and reach.

Recommendation 7: Develop a National Digital Research Infrastructure Strategy

An important driver for maintaining quality research output is Australia's ability to generate and analyse data as well as improving the digital skills of researchers. Digital research infrastructure is fundamental to Australia's research effort and requires a National Digital Research Infrastructure Strategy. The Strategy will coordinate and integrate the national digital research infrastructure ecosystem and underpin collaboration at scale. The Strategy will support researchers across all fields by providing the computing resources, digital tools, data governance frameworks and expertise needed to make best use of data. It will streamline access to data and address computing, storage and analysis needs for researchers. The Strategy should be consistent with, and supportive of, other whole of government initiatives in this area, such as the *Digital Economy Strategy* and *Australian Data Strategy*. The National Digital Research Infrastructure Strategy should be developed by government over the next year with any immediate insights feeding into the 2022 Research Infrastructure Investment Plan.

Recommendation 8: Prepare Australia to capitalise on future opportunities

The Expert Working Group recommends that Australia should enhance its sovereign capability with initial consideration given to the following NRI areas:

- cutting-edge national digital research infrastructure
- synthetic biology research infrastructure to deliver new bioindustries
- research translation infrastructure to drive increased industry investment
- world-leading environmental and climate infrastructure to underpin Australia's national adaptation strategy
- scoping future requirements to understand the opportunities of taking a national approach to collections.

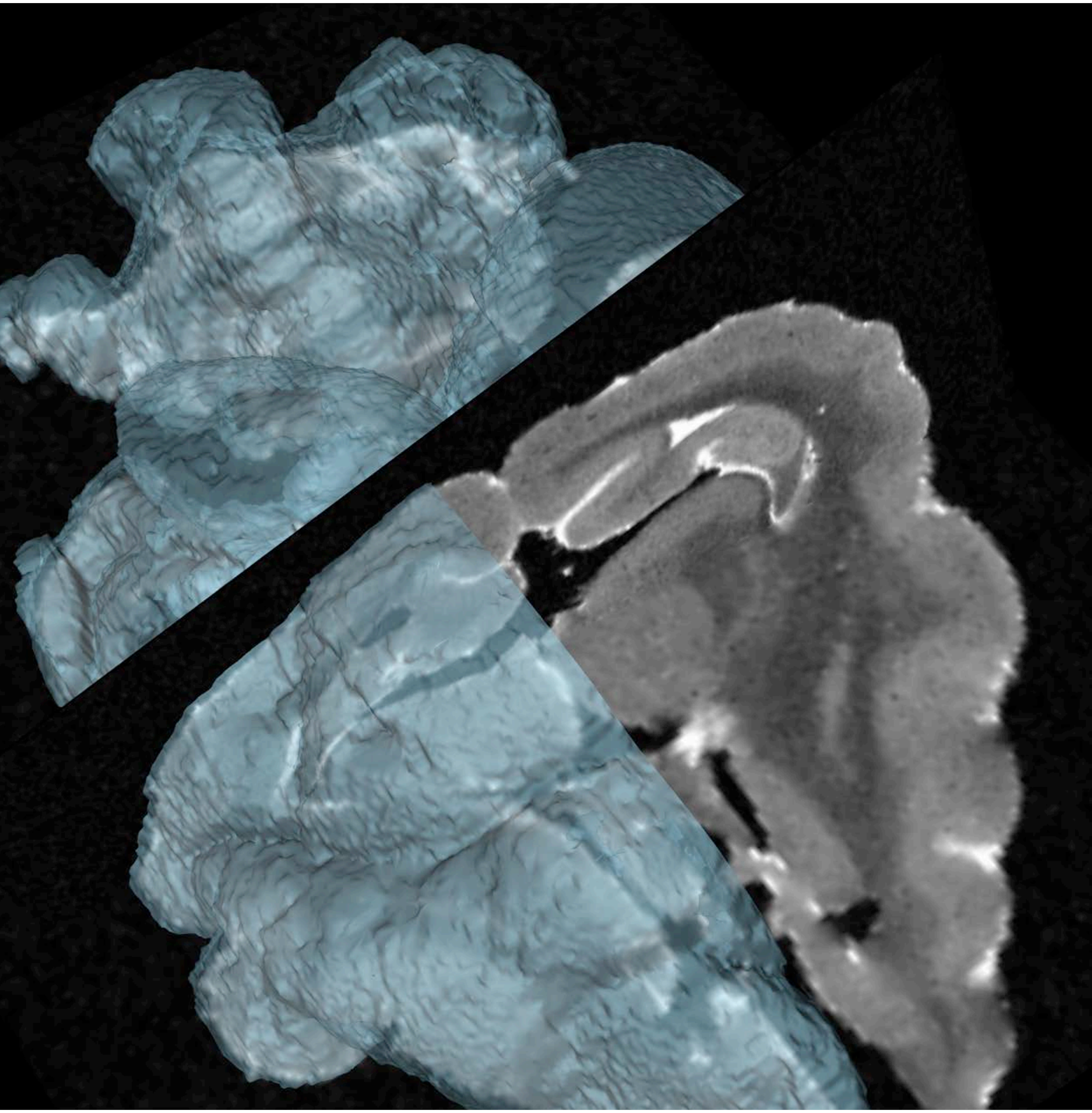


Image of the Thylacine 'Tasmanian Tiger' whole brain, acquired using the preclinical MRI facility at University of New South Wales node of National Imaging Facility. The thylacine is an extinct carnivorous marsupial that was native to the Australian mainland and the islands of Tasmania and New Guinea. It was the largest known carnivorous marsupial in the world prior to its extinction, evolving about 2 million years ago. The last known live animal was captured in 1930 in Tasmania. Image credit: National Imaging Facility

1

Introduction

1.1 Purpose of the Roadmap

The 2021 National Research Infrastructure Roadmap (Roadmap) sets the strategic direction and vision for Australian national research infrastructure (NRI) over the next five to ten years. As the key policy document addressing Australia's NRI requirements, the 2021 Roadmap provides guidance to government on actions that will enable researchers to maintain excellence, increase innovation and address emerging challenges. It continues the important trajectory of previous Roadmaps and reflects on the substantial contribution of our current NRI to Australia's research and innovation system.

After wide consultation with stakeholders, the 2021 Roadmap outlines a range of major challenges and emerging NRI issues and opportunities. The challenges reflect what researchers will be called on to address and strongly align with the Australian Government's *Modern Manufacturing Strategy*[1], *National Climate Resilience and Adaptation Strategy*[2], *Science and Research Priorities*[3], the *Blueprint for Critical Technologies*[4], *Australia's Long-Term Emissions Reduction Plan*[5] and the *University Research Commercialisation Scheme*[6]. Key areas for NRI enhancement and investment over the next five to ten years have been identified to support these challenges and are discussed in Chapters 3–6.

Future enhancement and investment in NRI will need to be sensitive to the potential for change built into government initiatives. For example, the *Blueprint for Critical Technologies* is clear on the potential for technologies to enhance or pose a risk to Australia's national interests. Investment in NRI must therefore consider Australia's economic prosperity, social cohesion and national security.

The relationship between chapters is represented in Figure 1. *Chapter 3: Research themes and challenges* outlines eight key research themes and challenges as a launching point to discuss the indicative NRI needed to address challenges. *Chapter 4: Opportunities for system-wide enhancements in NRI* identifies infrastructure opportunities relevant to the whole NRI system and *Chapter 5: Building on a strong NRI foundation* identifies operational enhancements to the NRI ecosystem. *Chapter 6: Potential for step-change* focuses on large step-change investments to create new Australian sovereign capabilities.

1 Department of Industry, Science, Energy and Resources, ***Modern Manufacturing Strategy***, Australian Government, 2020.

2 Department of Agriculture, Water and the Environment, ***National Climate Resilience and Adaptation Strategy 2021–2025***, Australian Government, 2021.

3 Department of Industry, Science, Energy and Resources, ***Science and Research Priorities***, Australian Government, 2015.

4 Department of the Prime Minister and Cabinet, ***Blueprint for Critical Technologies***, Australian Government, 2021.

5 Department of Industry, Science, Energy and Resources, ***Australia's Long-Term Emissions Reduction Plan***, Australian Government, 2021.

6 Department of Education, Skills and Employment, ***University Research Commercialisation Scheme***, Australian Government, 2021.

Figure 1. Overview of 2021 NRI Roadmap

Research themes and challenges (Chapter 3)

- Resources Technology and Critical Minerals Processing
- Food and Beverage
- Medical Products
- Recycling and Clean Energy
- Defence
- Space
- Environment and Climate
- Frontier Technologies and Modern Manufacturing

Indicative NRI investment

System-wide NRI enhancements to support challenges (Chapters 4 and 5)

- Continental-scale observations
- Large-scale integrated datasets
- Physical collections and biobanking
- Software analysis tools and platforms
- Bridging innovation gaps with translation NRI
- National digital research infrastructure strategy
- Governance – operational and workforce
- Indigenous knowledges and NRI
- HASS and NRI
- Industry engagement and research translation

NRI ecosystem investment and enhancements

Step-changes to support challenges (Chapter 6)

- Cutting edge national digital research infrastructure
- Research translation infrastructure to drive increased industry investment
- A national approach to collections
- Synthetic biology research infrastructure to deliver new bioindustries
- World-leading environmental and climate infrastructure to underpin Australia's national adaptation strategy

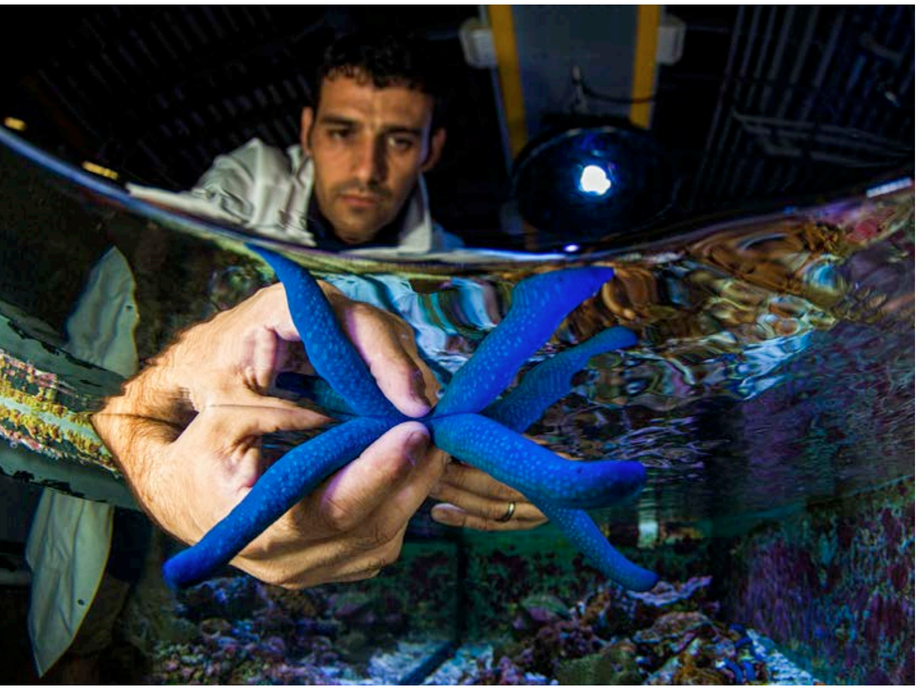
Large NRI investments and opportunities

1.2 NRI definition

The 2021 Roadmap modifies the definition of NRI used in the 2016 Roadmap[7] to reflect the importance of the NRI workforce in supporting research undertaken using NRI.

NRI comprises the nationally significant assets, facilities, services and associated expertise to support leading-edge research and innovation. It is accessible to publicly and privately funded users across Australia and internationally.

1.3 Role of NRI in the broader ecosystem


SeaSim Technician Eduardo Arias with a Blue Linkia starfish (*Linkia laevigata*), a common reef inhabitant on the Great Barrier Reef © AIMS Credit: Christian Miller

NRI plays a vital role in Australia's research and innovation ecosystem, optimising the use of resources and creating scale through nationally networked and accessible infrastructure. It supports researchers across the research pipeline (from fundamental to applied) and enables them to make the critical discoveries that drive innovation and economic growth and improve social outcomes.

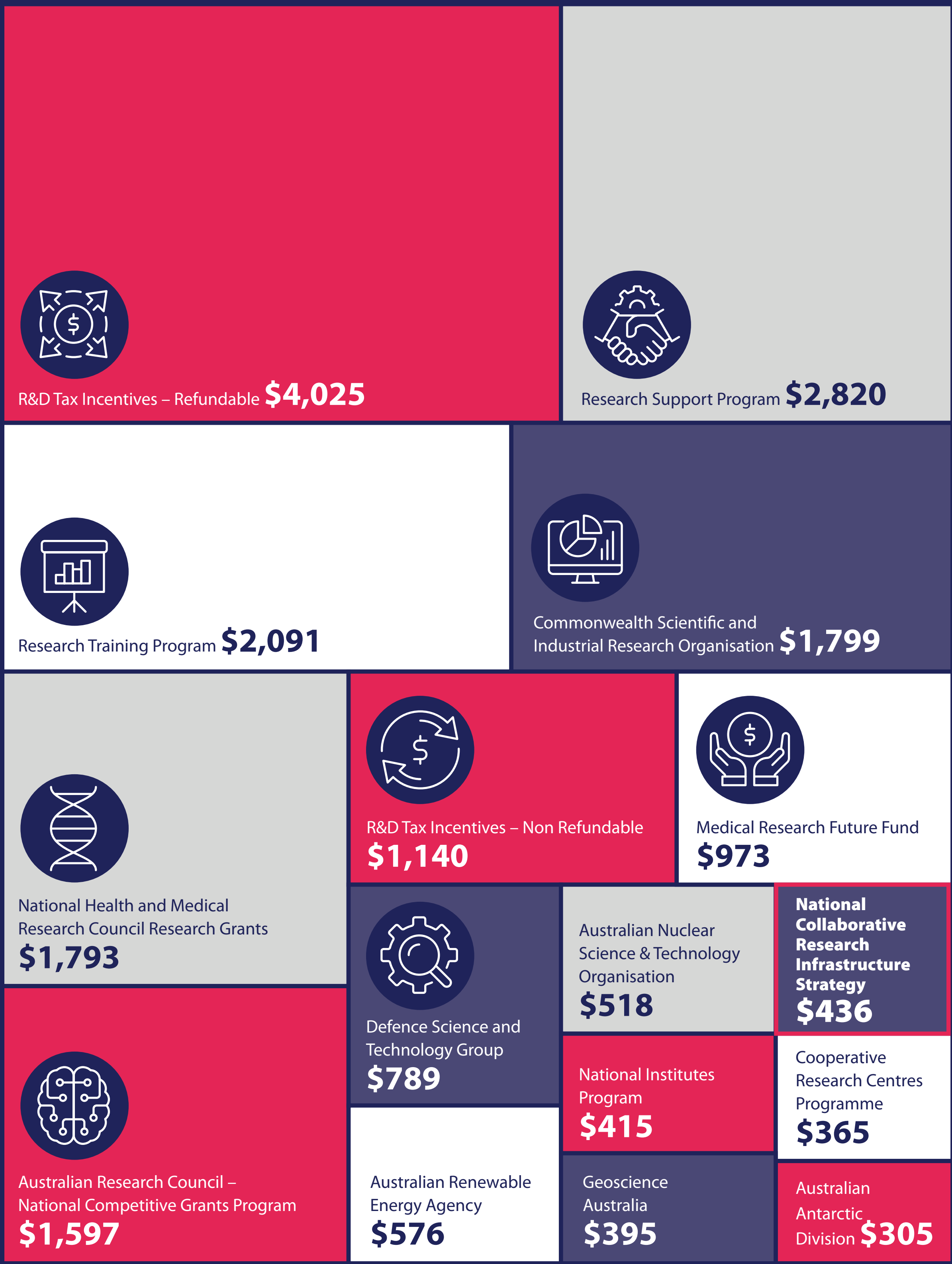
Public investment in research infrastructure supports collaboration and linkages across the innovation system, fosters multidisciplinary approaches and increases opportunities for research translation. In addition to economic benefits, innovation also contributes to improvements in living standards through advances in health care and education. These are critical outcomes as the government seeks to maximise the benefits of publicly funded research for society.

NRI funding is mainly provided through the Australian Government's National Collaborative Research Infrastructure Strategy (NCRIS) program. This program sits within a broader national ecosystem of science, research and innovation (SRI) initiatives that also support research infrastructure.

Figure 2 illustrates the programs and funding provided, including NCRIS and other SRI programs over the period 2019–21.

7 Australian Government, ***2016 National Research Infrastructure Roadmap***, Australia, 2016.

Figure 2. SRI Budget Tables by program ($ million), 2019–21[8]



8 Department of Industry, Science, Energy and Resources, *SRI Budget Tables 2020-21*, Australian Government, 2021.

Australia's research infrastructure system is comprised of four layers that work together as an ecosystem (Figure 3, as illustrated in the 2016 Roadmap).

Funding to support these layers goes beyond the NCRIS program. Institutional infrastructure reflects the facilities and services typically provided by the university sector. Funding for landmark and global research infrastructure, such as the Australian Synchrotron and the Square Kilometre Array, is provided through a range of Australian Government portfolios. State and territory governments, universities and the private sector also support the national infrastructure layer.

The 2011 NRI Roadmap[9] defined landmark investment as: *large-scale facilities (which may be single-site or distributed) that serve large and diverse user communities, are generally regarded as part of the global research capability, and engage national and international collaborators in investment and access protocols.*

Figure 3. Australian research infrastructure 'layers'

Institutional
Smaller scale infrastructure initiated at an institutional level and not in scope for the 2021 Roadmap

National
Nationally significant assets, facilities and services to support leading-edge research and innovation

Landmark
Large scale facilities that serve diverse communities and need international collaboration

Global
Multinational, collaborative infrastructure of a scale where cost of establishment is beyond the means of a single nation

9 Department of Innovation, Industry, Science and Research, ***2011 Strategic Roadmap for Australian Research Infrastructure***, Australian Government, 2011.

Alongside these critical investments are broader issues influencing Australia's NRI landscape that will require an ecosystem approach to resolve and optimise. There are structural, funding and policy settings that could be enhanced to support efficiencies across the research infrastructure layers, including:

- researcher training
- open science strategies including open access to research literature
- workforce skills and career pathways for research infrastructure staff
- integration of data and computing resources across institutional and national layers
- future research infrastructure co-investment.

1.4 NRI Principles

Recommendation 1: Adopt the NRI Principles

The Principles presented in this Roadmap outline the objectives for NRI investment. The 2021 Principles have been developed in recognition of rapid changes in the research and technology landscape. They are designed to assist decision-making that will protect Australia's interests and build capacity where there is a need to strengthen sovereign capability. Specific Investment Principles have been developed to align opportunities for planning and co-investment with research and industry partners, as well as state and territory governments. The Principles should be adopted by government and implemented in the 2022 Research Infrastructure Investment Plan.

The 2021 Roadmap provided an opportunity to review the NRI Principles so that they meet the evolving needs of modern research. A robust set of NRI Principles is required for articulating the government's objectives for investment and to focus endeavour. The 2021 NRI Principles build on those articulated in previous Roadmaps.

The 2021 Principles outline the objectives for NRI investment and include a separate set of NRI Investment Principles to help guide future funding decisions. The Investment Principles seek to emphasise the importance of planning and co-investment with research and industry partners, as well as state and territory governments.

NRI Principles

- NRI maximises the capability of the research and innovation system to contribute to economic outcomes, national security, social wellbeing and environmental sustainability.
- Research infrastructure is collaborative and planned in a way to provide a network of capabilities that serve the national interest and are aligned with government priorities.
- NRI includes people, skills and knowledge, data, processes and equipment.
- NRI resources are focused to achieve maximum impact in national priority areas.
- NRI is managed to deliver maximum impact as efficiently as possible. Synergies with complementary and related capabilities drive an ecosystem of support for researchers.
- NRI is widely accessible to researchers and industry across Australia. Barriers to access are as low as practicable.
- NRI enhances participation of researchers in, and provides access to, the international research system.
- NRI is respectful to Indigenous cultures and knowledges, and adopts the principles of Indigenous self-determination, leadership, impact and value, and sustainability and accountability as outlined in the AIATSIS Code of Ethics for Aboriginal and Torres Strait Islander Research.

NRI Investment Principles

- Funding for investment in NRI is in areas of national significance that can demonstrably support Australia's research and innovation system.
- Investment should balance the long-term nature of NRI development, together with changes in national priorities and identified gaps in the research and innovation system.
- Investment should produce NRI that facilitates and enhances industry and international engagement.
- Investment cases describe the intended impact and reflect the resources and governance needed to develop and manage world-class research infrastructure capability. These include the equipment, processes, data, skills and knowledge needed to deliver maximum value.
- Investment encourages and leverages opportunities for co-investment from states and territories, university, public and private sectors.
- Investment supports the development of a cohesive suite of NRI that strives to create an ecosystem of seamless services for researchers.

2

Current context

> NRI supports Australian and international researchers, facilitating communities of practice and best practice data generation, curation and storage. Australia is well-positioned to further enable this rapidly changing, interconnected digital research environment.

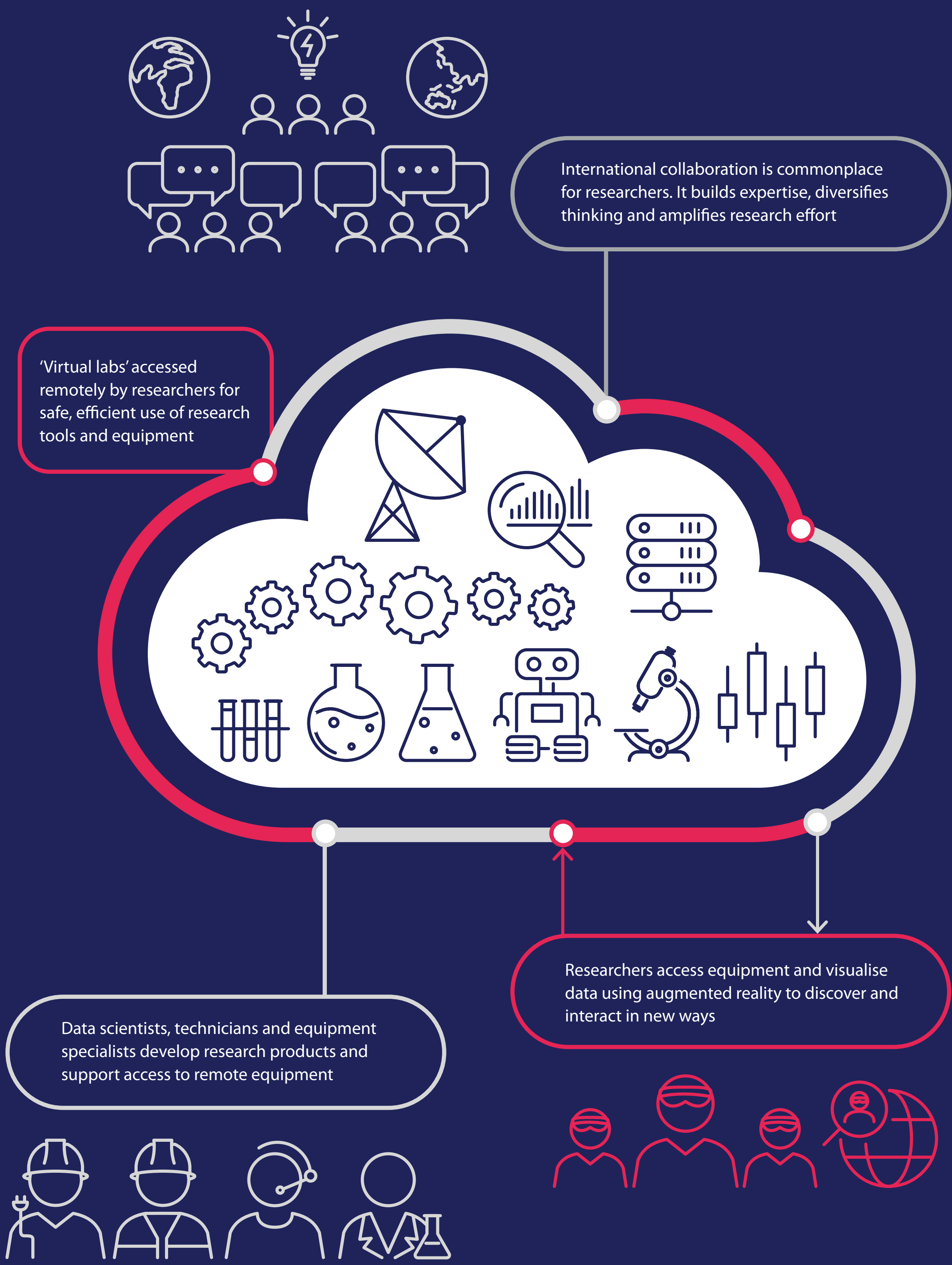
2.1 Emerging trends and areas

New techniques and technologies are changing the practice of research. The boundaries between the physical and digital world are blurring and meeting modern research challenges requires specialised skills and expertise across disciplines. Figure 4 depicts the characteristics of emerging research practice.

Emerging research trends will drive current and future NRI needs and investment opportunities. The consultation process for the 2021 Roadmap identified the following emerging research trends:

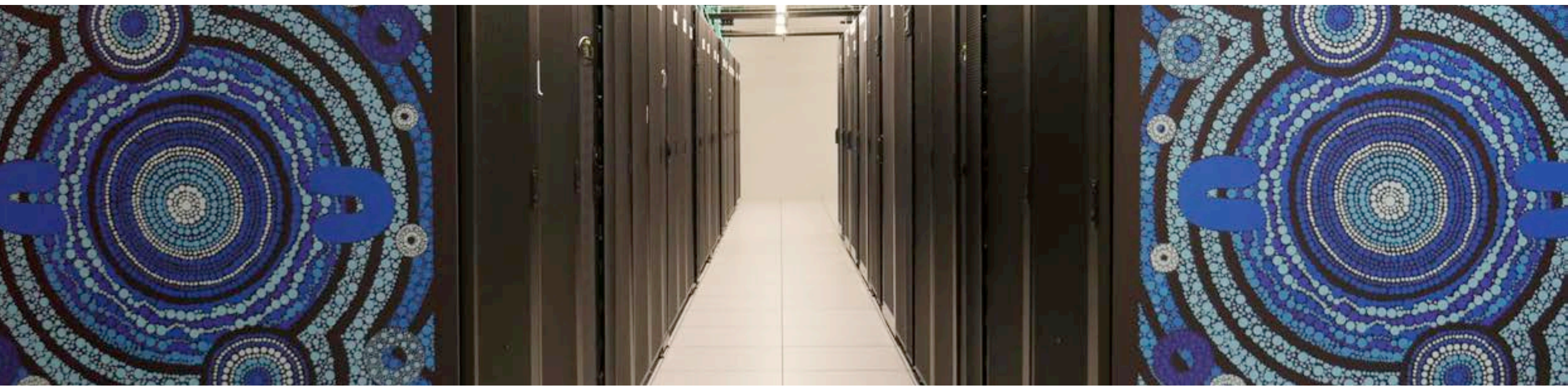
- The digital revolution is making modern research rapid and data intensive. Technological advances (artificial intelligence/machine learning (AI/ML), internet of things (IoT) and automation) are accelerating research outputs.
- Modern research is open, global, collaborative and increasingly mission driven. Convergent and multidisciplinary research is necessary to address complex challenges.
- Open access to research results and data (e.g. through open access publishing models) supports more collaborative and inclusive research practices (such as citizen science and industry engagement).
- There is growing appreciation of the critical role of the creative arts, humanities and social sciences in successfully addressing global challenges.
- Access to high-quality datasets requires strong national leadership, direction and coordination to deliver systematic data management and archival mechanisms.
- Researchers of the future will expect a seamless ecosystem of facilities and services. Interfaces will be easily accessible, with no separation between physical instrumentation, digital tools and the necessary supporting skills and expertise.
- Researchers will design and test on computers before starting physical experimentation and laboratories will be augmented by sensors, robotics and AI/ML.
- Human capital is vital, with both technical expertise and a skilled workforce becoming increasingly important. Progressively complex instrumentation and exponentially growing datasets necessitate collaboration between researchers and well-trained technical experts to best utilise research infrastructure and interpret results.
- Increased collaboration, both within and between different research areas and with industry, will require facilities to be multipurpose and serve many disciplines and industries.

Figure 4. Characteristics of emerging research practice



As well as the trends listed above, Roadmap consultations identified a range of emerging technologies and research areas of increasing prominence and national importance. These include:

- *Indigenous knowledges* – there is increasing awareness and recognition of the potential for Indigenous knowledges to help solve some of our biggest research challenges. Indigenous cultures and practices can guide development and sustainable use of Australian lands and waters[10].
- *Next generation omics* – integrated genomics, phenomics, transcriptomics, proteomics and metabolomics employ cutting-edge methodologies, such as analysis of single cells. These techniques underpin a range of research areas, such as environmental DNA (eDNA) monitoring and bioprospecting, precision medicine and agriculture.
- *Quantum technology* – quantum science and technology is increasing in importance. Advances in areas such as quantum sensing and computing will drive revolutionary changes across a range of technologies to enable and support discovery of valuable ore deposits, efficient groundwater monitoring and accelerated drug development through quantum chemistry simulation[11].
- *Synthetic biology* – the application of engineering principles to biology and involves the design and construction of biological systems and devices. Recent advances, such as the decreased cost of genome sequencing, process automation and increased computational power, are expanding potential applications. These include developing mRNA vaccines, engineering viruses to target antibiotic-resistant bacteria and developing unique organisms for environmental remediation.
- *Advanced climate modelling* – greater detail and granularity are required to identify which climate risks will most severely affect Australians, when and where they will happen and how they can be effectively managed. This will improve our understanding of climate systems and enable greater accuracy in predicting the impact of future climate changes.
- *Earth observation from space* – such observation is used for weather prediction and climate studies, environmental monitoring, mining and decision-making in agriculture and resource management. Greater capability in this area will improve policy settings and management of natural environments and generate agricultural and industrial development opportunities.
- *Materials science and advanced manufacturing* – synthesis, processing, characterisation of novel materials and computational capabilities have advanced significantly in the last decade, accompanied by development of nanomaterials, biomaterials, lasers, additive manufacturing materials, semiconductors and superconductors.
- *Renewable energy systems* – the long-term reliability of Australia's energy supply depends on improving existing energy infrastructure and diversifying energy resources. This includes examining the social and economic drivers of technology adoption, as well as the sources, infrastructure and systems surrounding these technologies.



Looking down the aisle between two pods of the Gadi supercomputer, the most powerful in the Southern Hemisphere.
Image credit: National Computational Infrastructure, Canberra

10 Woodward, E., Hill, R., Harkness, P. and R. Archer (Eds) 2020 *Our Knowledge Our Way in caring for Country: Indigenous-led approaches to strengthening and sharing our knowledge for land and sea management. Best Practice Guidelines from Australian experiences.* NAILSMA and CSIRO.

11 CSIRO, ***Growing Australia's Quantum Technology Industry: Positioning Australia for a four billion-dollar opportunity***, Australian Government, 2020.

2.2 International context

Australia must continually monitor global research infrastructure trends to identify best practice and provide the most effective conditions for supporting research excellence. In development of the 2021 Roadmap, it was critical to understand the global research and research infrastructure issues that are shaping the global environment and driving investment[12].

In the United Kingdom (UK), Europe, the United States of America (USA), Canada and Japan, research infrastructure investment planning ranges from three to five years, like Australia's five-year Roadmap cycle. These countries use similar roadmap processes to guide research infrastructure investment and align with national research strategies. International roadmaps are using missions and grand challenges to strategically align research and research infrastructure to deliver more effective impact.

Coordinated national digital research infrastructure (NDRI) strategies are becoming increasingly important as datasets grow exponentially and the demand for digital research skills increases. Some countries are using single entities and specific funding streams to coordinate NDRI in recognition of its central role across all research fields. For example, the Digital Research Alliance of Canada will coordinate, fund and promote the high performance computing, data management and research software components of the Canadian NDRI strategy. The European Open Science Cloud was established as a federated environment for hosting and processing research data at a pan-European scale.

Open science strategies, which many countries use to drive the adoption of open science principles, depend on well-connected digital research infrastructure (DRI) to manage open data. As well as supporting independently coordinated national DRI strategies, the open science trend has led to the development of global open science clouds and commons and open access publishing models. Such initiatives will likely increase the federation of research infrastructure in the digital domain.

Internationally, novel humanities, arts and social science (HASS) research infrastructure provides different arrangements of data custody, new data and large scales of data that foster new research practices. The distributed character of collections relevant to the cultural, humanities and social sciences (which involve datasets that are sensitive and predominantly unstructured and text-based) means that infrastructure arrangements require specialised expertise. Investment is typically directed towards constructing new data infrastructure. This brings together varied types of data (such as administrative, social media and digital heritage) and novel data exploitation using advanced computing tools and specialised informaticians. Such infrastructure creates the capacity to tackle research that it is not possible without investment in large-scale research infrastructure. The European experience shows:

- the importance of staged investment over time
- the need for careful consideration of governance and co-investment models
- the importance of participating in international collaborations.

Issues around funding sustainability are common internationally. Like Australia, research infrastructure is usually considered a long-term investment, but often allocated on short term funding cycles (particularly for operations). Various national approaches are used to encourage research infrastructure to secure appropriate funding sources for different lifecycle stages. For example, the UK's Research Partnership Investment Fund requires matched infrastructure and capital project funding from non-public investors.

12 Australian Academy of Science, *International Trends in Research Infrastructure Investment*, Department of Education, Skills and Employment, Australian Government, unpublished, 2021.

New and existing research infrastructure will require step-changes that incorporate technological advances to enable a higher level of performance, such as exascale and quantum computing. In the 2018 UK Research and Development Roadmap[13], UK Research and Innovation (UKRI) identified a range of capabilities which underpin research in multiple domains, including:

- advanced materials
- data analysis and software
- imaging and characterisation
- longitudinal datasets
- reliable and secure data storage
- robotics and automation
- sensor technologies
- storage of physical collections.

UKRI highlighted these areas as opportunities for sharing expertise and capability.

Internationally, the demand for a skilled research infrastructure workforce is increasing. There is also increasing focus on digital research skills that deliver best practice in research data and software management. These essential staff need reward systems and career pathways that simultaneously support open science practice and their professional development.

The Australian Proteome Analysis Facility (APAF) at Macquarie University, part of the Bioplatforms Australia network of facilities enabled by NCRIS. Image credit: Joanne Stephan

13 UK Research and Innovation, ***UK Research and Development Roadmap***, 2021.

2.3 Current NRI

Recommendation 2: Provide continuity and long-term funding to NRI

Australia's current network of national research infrastructure has been extremely successful in supporting national priorities and international collaboration. Funding stability since 2017–18 has resulted in the development of a strong suite of NRI underpinned by a highly skilled workforce. This stability needs to be maintained in recognition of the long-term operations of NRI. Government should maintain or increase current funding levels for NRI beyond 2028–29.

The NCRIS program underpins Australia's investment in research infrastructure and is distinct in its emphasis on collaboration instead of competition. Current NRI includes high performance computing and modelling, data management and curation, observing and monitoring of terrestrial and ocean environments, fabrication and manufacturing and access to analysis and characterisation equipment. A list of NRI currently supported under NCRIS is provided in Appendix 1.

Since the 2016 Roadmap and 2017–18 announcement of longer-term funding for NRI, investment has produced a well-developed, collaborative and dynamic network of NRI that supports Australian and international researchers. During the 2019–20 bushfires, NRI provided critical data and computational resources for Australia's weather and climate modelling capability to help track bushfire hazards. Automated sensors and field surveys gave scientists unprecedented understanding of post-fire recovery and resilience of the Australian environment. As the world grappled with the challenges posed by the COVID-19 pandemic, Australia's investment in NRI supported the development and testing of sensitive diagnostic PCR tests, vaccines and manufacture of personal protective equipment.

Many NRI facilities are engaged in collaborative arrangements that support cross-disciplinary and convergence research. This includes significant collaboration between NRI and other elements of the innovation system to support researchers. NRI investment has assisted Australian researchers to participate in international collaborations and leverage access to world-leading facilities.

NRI supports outcomes across the range of government priorities and policy areas including climate, health, manufacturing and agriculture. In 2018–19, 76 per cent of current NCRIS projects provided critical or operational services to enable Australian Government policies and program delivery. A similar proportion of projects enabled program delivery by state governments (71 per cent, up noticeably from 43 per cent in 2017–18) and local governments (19 per cent)[14].

The NRI ecosystem has developed sufficiently that streamlining structural and governance arrangements may deliver greater efficiency. This could include integration of some services and functions. This would provide greater benefits to users through a more complete and seamless NRI system, with consistency in access arrangements and a greater range of services. This is discussed further in *Chapter 5: Building on a strong NRI foundation*.

14 Wallis, *NCRIS Census Report (2018-19)*, DESE, Australian Government, unpublished, 2021.

CASE STUDY

Stability helps guide the way through COVID-19's uncertainty

The arrival of COVID-19 posed many challenges globally, but Australia was well-placed to deal with its myriad challenges through the strength, stability and adaptability of its NRI network.

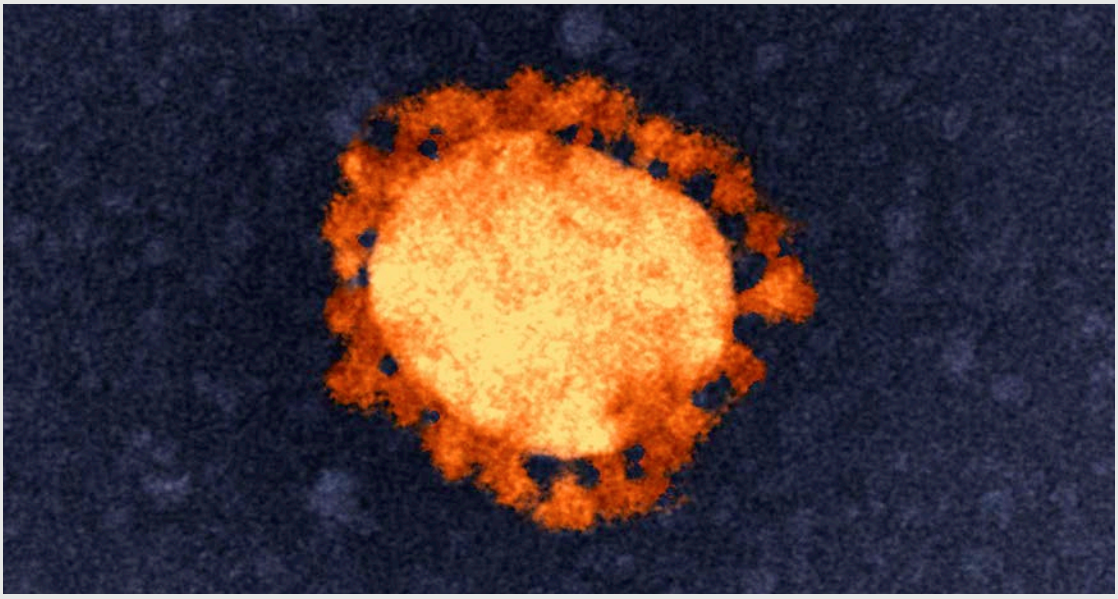
NRI already serves the varied needs of the research and innovation communities through cutting-edge equipment, expert advice and services. But in early 2020, all projects swiftly pivoted and redeployed across a spectrum of needs in response to the developing pandemic.

Responses from projects such as Therapeutic Innovation Australia, the Australian Centre for Disease Preparedness, Phenomics Australia and Bioplatforms Australia supported the early stages of research and diagnosis, including genomic analyses, animal models, development and testing of treatments and multiple vaccine candidates (up to and including Phase I clinical trials). The National Deuteration Facility manufactured important molecules for research.

Nuclear Science Facilities, Microscopy Australia and the National Imaging Facility supported the manufacture and validation of diagnostic kits and personal protective equipment for Australian health care workers, assessed construction, effectiveness and reusability of N95 masks, and 3D printed adjuncts for respirators as well as helping Australian companies develop low-cost, easy-to-use ventilators.

Importantly, NCRIS projects helped provide the data required to understand the pandemic and its impacts. The Population Health Research Network linked data was used to track, predict and respond to COVID-19's health and health care system impacts, while the Australian Urban Research Infrastructure Network helped researchers understand how the pandemic affected housing and employment vulnerability. These efforts specifically supported many state-based projects.

The depth and breadth of NRI's agility would not have been possible without long-term funding. This funding continuity provides the certainty necessary to keep building and renewing a strong and agile network of infrastructure, that can address unexpected major challenges that arise in the community.



This colour-enhanced image was among the first in the world showing the external structure of the novel coronavirus, SARS-CoV-2. It was taken on the transmission electron microscope in the high-containment lab at CSIRO's Australian Centre for Disease Preparedness (a Microscopy Australia linked lab) in early 2020. Image credit: CSIRO.

2.4 International collaboration

Australia has a strong history as a partner and leader in international research. NRI has an important role in supporting international linkages and contributing to the production and dissemination of research knowledge. Many NRI facilities are involved in international collaborations, either multilaterally or bi-laterally. These partnerships occur at various levels, ranging from institutional to government-to-government.

NRI is assisting Australian researchers to engage in a broad range of existing global research infrastructure initiatives, including:

- Square Kilometre Array
- European Molecular Biology Laboratory
- Global Ocean Observing System
- Giant Magellan Telescope
- International Ocean Discovery Program
- International Mouse Phenotyping Consortium
- Global Bioimaging
- Research Data Alliance.

The Milky Way provides both a spectacular backdrop, and a hunting ground for CSIRO's Australian Square Kilometre Array Pathfinder (ASKAP) radio telescope. Image credit: CSIRO

The primary drivers for Australia to participate in global research infrastructure projects are:

- leadership and direction setting, particularly in new or emerging areas
- opportunities for researchers and Australian NRI experts to train and collaborate with the global research infrastructure community
- strategic engagement in areas where we have expertise, such as astronomy and space instrumentation
- large-scale collaborations particularly in the areas where data is a significant enabler, such as environment and health
- alignment with the national interest or national priorities
- cost effectiveness, as many projects are on a financial scale and of technical complexity that is beyond the reach of most individual countries, such as gravitational wave detectors and particle colliders.

NCRIS projects are engaged in formal and informal collaborative arrangements with organisations around the world. International engagement includes Memorandums of Understanding, visits to and from international facilities, representation on expert working groups and invitations to speak at international conferences. This has resulted in access to data and expertise and amplified NRI investment.

2.5 Developments since 2016 Roadmap: scoping studies

The 2016 Roadmap identified specific research areas requiring further scoping work to better understand emerging research infrastructure needs. Eight scoping studies were supported in the 2018 Investment Plan. The outcome of three scoping studies provided valuable input to the 2020 Investment Plan and resulted in three pilot projects:

- expansion and upgrade of the Australian Community Climate and Earth Systems Simulator (ACCESS-NRI)
- developing targeted HASS and Indigenous data tools and platforms
- synthetic biology (biofoundry), a new infrastructure that will help researchers create new biological parts and systems more efficiently.

Feedback on the remaining five scoping study areas was sought during the Roadmap's development. Two scoping study discussion papers (National Environmental Prediction System (NEPS) and Precision Measurement) were released for consultation. High performance computing (HPC) issues were included in stakeholder discussions on data and computing needs. Biobanking and biosecurity issues were raised in the NRI survey and discussed with government agencies and key stakeholders.

Outcomes from these consultations have been incorporated into Chapters 3–6.

3

Research themes, challenges and NRI impact

Eight themes emerged from the Roadmap consultations as the likely focus of Australian research over the next five to ten years. Within each theme is a key challenge for research to address. The themes and challenges strongly align with the objectives of the government's *Modern Manufacturing Strategy*, the *National Climate Resilience and Adaptation Strategy*, the *Science and Research Priorities*, the *Blueprint for Critical Technologies, Australia's Long-Term Emissions Reduction Plan* and the *University Research Commercialisation Scheme*.

This challenge-focused approach to identifying NRI and its impacts is consistent with the approaches of international roadmaps. Though the challenge framework aims to link the NRI system with the national research effort, support for fundamental research and research excellence more broadly remains a critical function of NRI.

Recommendation 3: Adopt a challenge framework to support NRI planning and investment

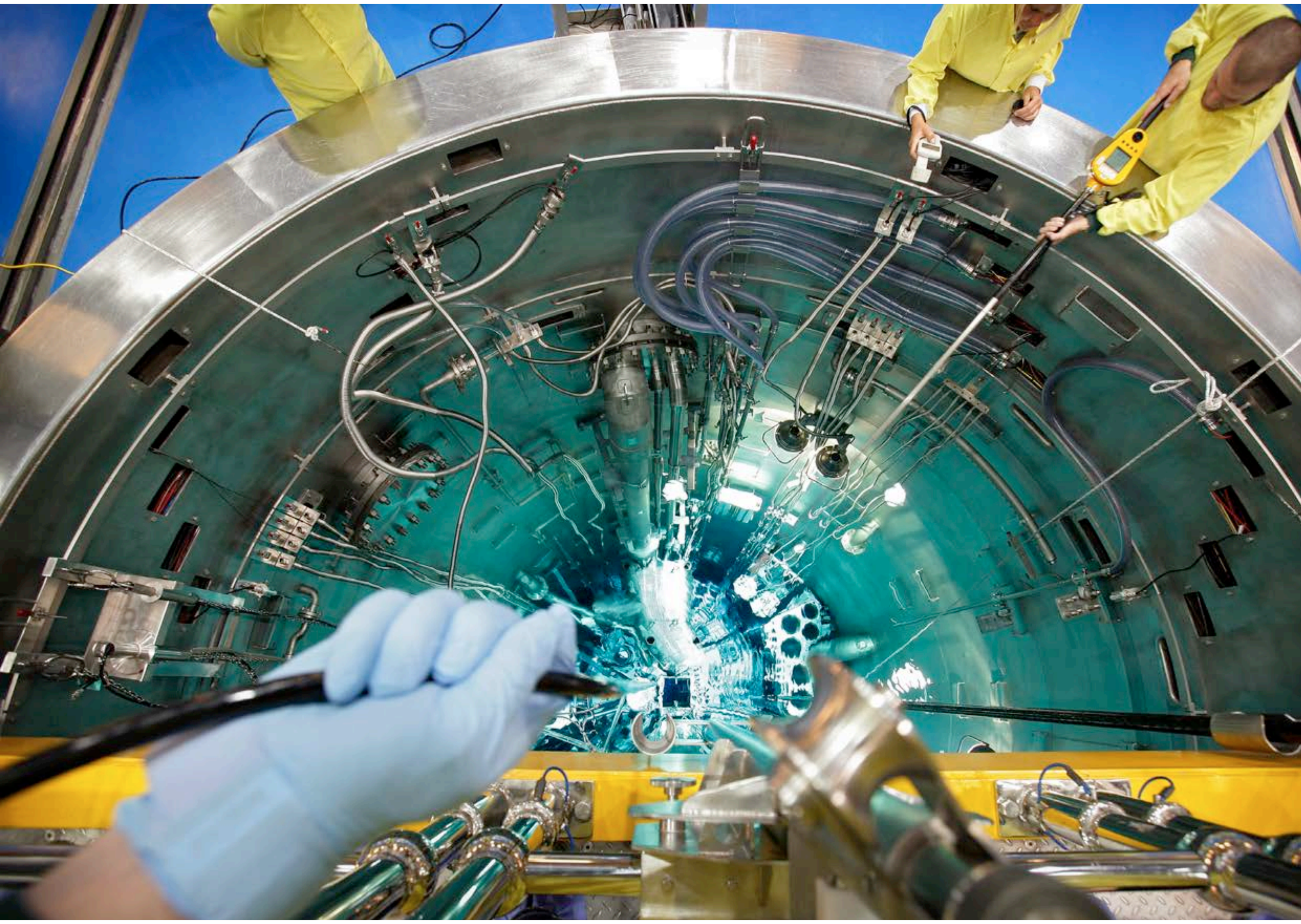
The 2021 Roadmap identified key challenges that have significant impact for Australia and around the world. Using a challenge framework to support NRI planning and investment will assist our research effort to address the big issues facing Australia. The challenges below aim to focus research efforts and attract co-investment in the necessary research infrastructure to increase Australia's economic prosperity and improve the lives of individuals.

- *Resources Technology and Critical Minerals Processing* – We are a global resources leader stemming from our rich natural resource endowments, huge investments in R&D, proximity to the growing Asian market and a skilled workforce. We can leverage these strengths in combination with our vast critical minerals endowments to deliver critical enablers for a range of sectors.
- *Food and Beverage* – Our success is underpinned by our international reputation for premium, safe and high-quality food and beverage products, strong production capabilities, research expertise and market proximity.
- *Medical Products* – We have strong medical research capability, a reputation for quality and standards and proximity to emerging markets in Asia with rapidly aging demographics and a growing middle class.
- *Recycling and Clean Energy* – We have strong circular economy research capabilities, as well as world-class solar and wind resources and a well-established minerals industry and skills base. We also have a large land mass to build on and experience in delivering large energy projects.
- *Defence* – Defence exports are growing, with a focus on increasing the international competitiveness and success of Australian defence industry. The sector provides advanced technology with cross-sectoral applications and delivers on our national security imperatives as outlined in the Defence Industrial Capability Plan.
- *Space* – Space technologies enable activity across the economy. Our emerging global position is underpinned by research expertise, geographical location, cutting-edge facilities and advanced manufacturing capabilities.
- *Environment and Climate* – Our future prosperity will be safeguarded by positioning Australia to better anticipate, manage and adapt to our changing climate.
- *Frontier Technologies and Modern Manufacturing* – Developing and translating critical technologies required to support modern manufacturing and secure supply chains. Success will include investment in research and commercialisation of critical technologies.

The themes and challenges, together with indicative research infrastructure required to support researchers to deliver on them, is discussed in this chapter and summarised in Figure 5. Although infrastructure needs are siloed under challenges, much of this infrastructure has broader application and can be used to solve many problems. For example, 'omics facilities' relates to health, environmental and agricultural outcomes but is listed under 'Frontier Technologies and Modern Manufacturing'.

The research infrastructure identified in Figure 5 is indicative and serves to start discussion of current and future NRI needs through the Roadmap. Some of this infrastructure features in *Chapter 4: Opportunities for system-wide enhancements in NRI* and *Chapter 5: Building on a strong NRI foundation* as part of NRI system-wide opportunities and enhancements, and then again in *Chapter 6: Potential for step-change* as critical elements of the step-change NRI investments.

Figure 5 does not reflect all underpinning NRI such as data and computing infrastructure, metrology and precision measurement, particle accelerators and ion beams. These cross-cutting NRI are necessary to deliver research outcomes across the challenges and are core NRI functions (see *Chapter 3.9: Current NRI support for research challenges*).

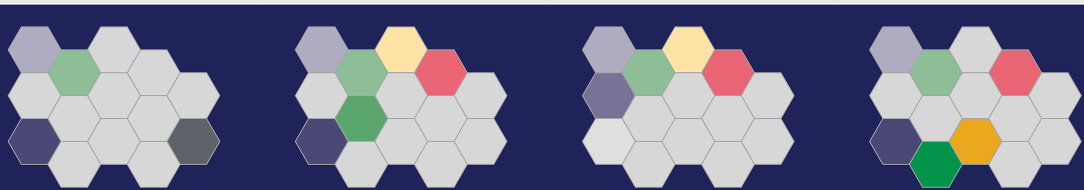


A view of the state of the art 20 MW(t) multipurpose reactor OPAL from above. The reactor core is located in a 12.6 metre deep reactor pool of demineralised light water. Image credit: Australian Nuclear Science and Technology Organisation

Figure 5. 2021 NRI Roadmap themes and challenges

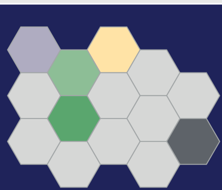
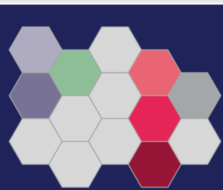
Theme	1. Resources Technology and Critical Minerals Processing	2. Food and Beverage	3. Medical Products	4. Recycling and Clean Energy
Key challenge to be addressed	We are a global resources leader stemming from our rich natural resource endowments, huge investments in R&D, proximity to the growing Asian market and a skilled workforce. We can leverage these strengths in combination with our vast critical minerals endowments to deliver critical enablers for a range of sectors.	Our success is underpinned by our international reputation for premium, safe and high quality food and beverage products, strong production capabilities, research expertise and market proximity.	We have strong medical research capability, a reputation for quality and standards and proximity to emerging markets in Asia with rapidly aging demographics and a growing middle class.	We have strong circular economy research capabilities, as well as world-class solar and wind resources and a well-established minerals industry and skills base. We also have a large land mass to build on and experience in delivering large energy projects.
Research Infrastructure required to address challenge	▪ Geological precision analysis equipment ▪ Integrated national geo-mapping data ▪ Multi-purpose mineral and material processing facilities	▪ Facilities for crop and livestock phenotyping and genome improvement ▪ Open-source national agricultural data infrastructure ▪ Biocontainment facilities for pathogen and pest research	▪ National integration of large-scale health datasets ▪ Biologics development facilities ▪ Small molecule designing, synthesis, testing and drug development facilities ▪ Facilities supporting nuclear medicine and radiotherapy ▪ National facilities supporting pre-clinical and clinical research	▪ Advanced renewable and other zero emissions technology development facilities ▪ Hydrogen energy development and storage testing facilities ▪ Publicly accessible national energy database

Links to national priorities



National priorities

- Science and Research Priorities
- Australian Medical Research and Innovation Priorities
- Australia's Long-Term Emissions Reduction Plan
- Modern Manufacturing Strategy
- National Agricultural Innovation Agenda
- National Hydrogen Strategy

Theme	5. Defence	6. Space	7. Environment and Climate	8. Frontier Technologies and Modern Manufacturing
Key challenge to be addressed	Defence exports are growing, with a focus on increasing the international competitiveness and success of Australian defence industry. The sector provides advanced technology with cross-sectoral applications and delivers on our national security imperatives as outlined in the Defence Industrial Capability Plan.	Space technologies enable activity across the economy. Our emerging global position is underpinned by research expertise, geographical location, cutting-edge facilities and advanced manufacturing capabilities.	Our future prosperity will be safeguarded by positioning Australia to better anticipate, manage and adapt to our changing climate.	Developing and translating critical technologies required to support modern manufacturing and secure supply chains. Success will include investment in research and commercialisation of critical technologies.
Research Infrastructure required to address challenge	▪ Cybersecurity data ecosystem coordination, encryption technology ▪ Defence materials, components and equipment development	▪ Earth observation infrastructure ▪ Space exploration ▪ Optical and radio astronomy infrastructure and data storage ▪ Astronomy precision measurement infrastructure	▪ Biodiversity monitoring, collection and analysis infrastructure ▪ Networked environmental modelling infrastructure ▪ Integrated, publicly accessible environmental datasets ▪ Marine, coastal, freshwater, groundwater and atmospheric monitoring and observation infrastructure ▪ Climate modelling and adaptation infrastructure	▪ Robotics infrastructure ▪ Nanofabrication infrastructure ▪ Space-related manufacturing infrastructure ▪ Quantum technologies infrastructure ▪ Synthetic biology infrastructure ▪ Omics facilities ▪ Microscopy and advanced imaging facilities ▪ Support for user experience and human centered design
Links to national priorities				

National priorities

- National Climate Resilience and Adaptation Strategy
- National Security, Science and Technology Priorities
- Low Emissions Technology Investment Roadmap
- Defence Science and Technology Strategy
- Australia's Critical Minerals Strategy 2019
- Blueprint for Critical Technologies
- Australian Civil Space Strategy
- Sovereign Industrial Capability Priorities

3.1 Resources technology and critical minerals processing

Challenge: We are a global resources leader stemming from our rich natural resource endowments, huge investments in R&D, proximity to the growing Asian market and a skilled workforce. We can leverage these strengths in combination with our vast critical minerals endowments to deliver critical enablers for a range of sectors.

Australia is a world leader in mineral exports and has significant reserves of the critical minerals and resources that are used to manufacture products such as electric vehicles, mobile phones and renewable energy systems. Australia accounted for 49 per cent of the world's lithium production in 2020 and was the sixth-largest mined copper producer in the world. The resource sector contributes approximately 10 per cent of Australia's GDP and is expected to generate $349 billion in exports in 2021–22, accounting for more than 50 per cent of total national exports[15]. However, there are supply chain risks (as highlighted during the COVID-19 pandemic) which reveal the importance of critical minerals and our key role as a major producer. Australia significantly contributes to the supply chains of like-minded partners through commercial arrangements and offtake agreements.

Addressing this challenge aligns closely to government research priorities, including the *Science and Research Priorities* (Resources), the *Modern Manufacturing Strategy* (Resources Technology & Critical Minerals Processing), *Australia's Long-Term Emissions Reduction Plan* (Resources and Heavy Industry) and *Australia's Critical Minerals Strategy 2019*[16].

The development of new technologies and improved processing techniques will:

- reduce the costs of critical mineral extraction and downstream processing
- facilitate project development and investment opportunities
- generate projects focused on the recovery of critical minerals from unconventional materials and sources
- improve environmental impact.

Ultimately, this would allow Australia to be a trusted global supplier of critical minerals and support high-paying job opportunities and regional development.

Australia has robust environmental, social and governance standards. Australia is a founding partner of the Energy Resources Governance Initiative[17] along with Canada, Peru and the USA, and is working with like-minded countries through the International Standards Organisation to ensure international standards support ethical, sustainable and secure supply chains.

15 Department of Industry, Science, Energy and Resources, ***Resources and Energy Quarterly***, Australian Government, 2021.

16 Department of Industry, Innovation and Science and Australian Trade Commission, ***Australia's Critical Minerals Strategy 2019***, Australian Government, 2019.

17 Governments of Australia, Botswana, Canada, Peru and the United States, ***Energy Resource Governance Initiative (ERGI)***, 2019.

Researchers are improving the fundamental understanding of the structure, composition and processes governing the formation and distribution of resources in Australia. This research supports improvements in critical mineral processing and finding deeper and more hidden critical mineral reserves. There is also increasing importance of research to improve our knowledge of the environmental impacts associated with resource extraction and the technologies that will deliver more effective and efficient resource extraction, processing and waste management[18]. We must continue to ensure the continued viability of supply chains through the availability of critical inputs, such as rare earths, water and other under-developed or constrained resource types.

Research to support the development of resources technology and the processing of critical minerals should be underpinned by the following research infrastructure:

- Geological precision analysis equipment
  - Geological precision analysis equipment such as isotopic analysis equipment, secondary-ion mass spectrometry, X-ray fluorescence and X-ray diffraction technologies can be used to conduct precision analysis of geological and water samples.
- Integrated national geo-mapping data
  - Integrated national geo-mapping data includes high resolution geoscience data and information about the potential mineral, energy and groundwater resources concealed beneath the surface. A national geo-mapping database will enable interoperability of data and support enhanced identification of sites with high prospects of containing critical minerals.
- Multipurpose mineral and material processing facilities
  - Mineral and material processing facilities provide support for efficient extraction of minerals and the transformation of raw inputs into value-added chemicals and materials. They also support the development of extraction technologies that will allow lower-grade ores to be mined economically. Such facilities include characterisation equipment to map the distribution of trace particles and impurities in samples, chemical and engineering equipment used in processing and datasets on optimal extraction techniques.

Georgina Gordon inspects drill cores from the Geological Survey of South Australia's Hylogger facility, which is enabled by NCRIS via AuScope. Image credit: AuScope.

18 Department of Industry, Science, Energy and Resources, *Science and Research Priorities*, Australian Government, 2015.

3.2 Food and beverage

Challenge: Our success is underpinned by our international reputation for premium, safe and high-quality food and beverage products, strong production capabilities, research expertise and market proximity.

Agricultural productivity must continue to grow in the face of constrained soil and water resources, climate change and threats from pathogens, pests and invasive species. Development of innovative food and fibre production and processing technologies will be key to ensuring continued growth in the agricultural sector. Innovation that transforms the properties of local produce (e.g. nutritional value and shelf life) will help Australia capitalise on growing global demand for premium food offerings.

As well as being negatively affected by climate change, agriculture contributes significantly to greenhouse gas emissions. Approaches aimed at minimising these emissions and improving efficiency must be developed and implemented for Australia to meet its emission reduction targets.

Addressing this challenge aligns with government priority frameworks, including the *Science and Research Priorities* (Food and Soil and Water), the *Modern Manufacturing Strategy* (Food & Beverage), the *Blueprint for Critical Technologies* (opportunity to help us solve agricultural and environmental issues), the *National Agricultural Innovation Agenda*[19], the *National Climate Resilience and Adaptation Strategy* and *Australia's Long-Term Emissions Reduction Plan* (Agricultural Industry).

Addressing this challenge has the additional benefits of:

- maintaining growth, in line with the goal for the agricultural sector to be worth $100 billion by 2030
- reducing the environmental impact of the sector by exploiting developments such as precision agriculture, non-meat-based proteins and 'methane-busting' seaweed feed supplements for livestock
- improving health outcomes by the production of high-quality nutritious food.

To achieve increased agricultural productivity, research is needed into identifying the genetic traits for increased resilience to drought, salinity, pests and pathogens, and incorporating these into crops and livestock. Increasingly, research using sensors and imaging is aimed at monitoring soil moisture content, nitrogen content, crop canopy height and plant health, as well as animal health.

Additionally, research into reducing inputs such as herbicides, pesticides and fertilisers, as well as optimising land management, will have environmental benefits such as carbon drawdown, landscape and biodiversity protection and reduced run-off into streams. More research is needed into the development of novel food sources such as alternative proteins, which could add $3 billion to the Australian economy by 2030[20]. Although there is well-established NRI for research into animal and aquaculture pests and pathogens, there is a need for integrated national containment facilities for plant pathogens. Australia's current and future export success depends on the production of clean, safe and nutritious food of known provenance from efficient, innovative and sustainable farming systems. It also requires strong and robust biosecurity systems to manage the risks of pests and diseases.

19 Department of Agriculture, Water and the Environment, ***National Agricultural Innovation Agenda***, Australian Government, 2021.

20 ACOLA, ***Future of Agricultural Technologies***, Australian Government, 2020.

Imaging stations such as the LemnaTec Scanalyzer 3D allow for the measurement of shoot area, estimated biomass, plant height and width, canopy density, other morphometric data and leaf colour. Other sensors allow the APPF to measure a range of plant constituents, including nutrients, water or other aspects of plant physiology. Image credit: Australian Plant Phenomics Facility

Research to increase agricultural productivity should be underpinned by the following research infrastructure:

- Facilities for crop and livestock phenotyping and genome improvement
  - Facilities for crop and livestock genome improvement and phenotyping would support the application of Australia's high-quality fundamental research in genetic engineering and gene editing to crops and livestock species.
- Open-source national agricultural data infrastructure
  - National agricultural data infrastructure will enable modelling of crop and livestock performance through collecting, analysing, integrating and sharing data on parameters such as soil moisture content, nitrogen content, crop canopy height and plant and animal health. This will enable efficient pest tracking, management of biosecurity risks and increased productivity in the face of constrained resources and environmental change.
- Biocontainment facilities for pathogen and pest research
  - Biocontainment facilities for pathogen research includes both PC4 and networked PC3 laboratories. Facilities to deal with plant pathogens and pests (including weeds) would complement Australia's current animal biocontainment facilities. A 'one health' approach to pathogen research protects Australia from both plant and animal biosecurity threats, and optimises health of people, animals and ecosystems.

3.3 Medical products

Challenge: We have strong medical research capability, a reputation for quality and standards and proximity to emerging markets in Asia with rapidly ageing demographics and a growing middle class.

The importance of protecting Australians from health threats has been highlighted by the COVID-19 pandemic. Improving health outcomes through novel medical products, platforms, technologies and practices has the potential to improve quality of life and decrease health-related costs. This includes smart monitoring devices and diagnostics, human imaging technologies, personalised implants, high value therapeutics, cutting-edge pharmaceutical and non-pharmaceutical treatments (e.g. regenerative medicine and genomics), digital integrated products and platforms, integrated health datasets and health interventions.

A scientist in a biocontainment suit, working at the Australian Centre for Disease Preparedness. Image credit: CSIRO

Addressing this challenge aligns with government priority frameworks, including the *Science and Research Prioritie*s (Health), the *Modern Manufacturing Strategy* (Medical Products), the *Blueprint for Critical Technologies* (opportunities for improved health and social outcomes), the *National Climate Resilience and Adaptation Strategy* (social/health domain) and the *Australian Medical Research and Innovation Priorities*[21].

Addressing this challenge has the additional benefits of:

- increasing cost effectiveness via preventative medicine
- securing national sovereignty and capturing more economic value in terms of therapeutic development. This is likely to involve greater onshoring of therapeutic discovery, development and manufacturing pathways.

Researchers can help improve Australia's health outcomes, meet growing demand for medical products and take advantage of other nations looking for new suppliers through a broad range of activities. For example, both fundamental and applied research into therapeutics leads to new and innovative treatments and disease prevention options. Precision medicine can change how health care is delivered by ensuring personalised treatments. Improved integrated datasets can be used to inform better models of health care and health services. Similarly, innovative research into the health impacts of climate change and ways of improving mental health can ensure continued community resilience.

Research to improve health outcomes should be underpinned by the following research infrastructure:

- National integration of large-scale health datasets
  - Health datasets include experimental outputs, large-scale genomic data, clinical data, population data and those relevant to social determinants of health (such as education and employment status). Disparate datasets could be integrated in an open access national platform, with appropriate privacy protections.
- Biologics development facilities
  - Biologics development facilities would support basic and translational research in biologics (e.g. mRNA vaccines, cell and gene therapies). This includes design, synthesis, testing and development.
- Small molecule designing, synthesis, testing and drug development facilities
  - Small molecule development facilities would support basic and translational research for small molecule therapeutics. This includes small molecule design, synthesis, testing and development.
- Facilities supporting nuclear medicine and radiotherapy
  - Nuclear medicine and radiopharmaceuticals are areas of fast-growing innovation that Australia is well-positioned to lead and that are underpinned by existing NRI. This includes the development of new radiopharmaceuticals for diagnosis and therapy (e.g. theranostics), supported by advanced human imaging.
- National facilities supporting preclinical and clinical research
  - Preclinical research support includes modelling for both disease mechanisms and early drug candidate testing, as well as medical imaging infrastructure. This is performed both in animal models and newer *ex vivo* and *in vitro* models. It is recognised that alternatives to animal models are becoming more prominent, but also that it is unlikely live models can be fully replaced for some time. With the current research infrastructure provider at risk, the need for reasonably urgent national consideration of animal model provision was identified through Roadmap consultations.
  - Clinical research support involves support for clinical trials and the development and evaluation of non-pharmaceutical therapeutic products such as implants, bionics and AI expert systems. The necessary infrastructure includes human imaging, genomics and the scale-up of drug production.

21 Department of Health, ***The Australian Medical Research and Innovation Priorities 2020–2022***, Australian Government 2020.

3.4 Recycling and clean energy

Challenge: We have strong circular economy research capabilities, as well as world-class solar and wind resources and a well-established minerals industry and skills base. We also have a large land mass to build on and experience in delivering large energy projects.

A reliable, sustainable and low-cost energy and fuel supply is essential to Australia's transition towards a net zero economy. Recycling and clean energy technologies can also help open export opportunities by capturing greater value from our intellectual property (IP). Remanufacturing can also address our waste problem and offer new opportunities with the increasing demand for sustainably produced goods.

To meet future demand while avoiding the by-products of our current energy and fuel sources, we must maximise resource recovery and find alternatives. These might include existing primary energy sources such as solar and wind electricity, and emerging fuels such as hydrogen. Australia has the resources and experience to take advantage of increasing global momentum for clean hydrogen with the International Energy Agency and the World Energy Council both identifying Australia as a potential leader in hydrogen production.

Addressing this challenge aligns with government priority frameworks, including the *Science and Research Priorities* (Energy), the *Modern Manufacturing Strategy* (Recycling & Clean Energy), the *Blueprint for Critical Technologies* (opportunities to address agricultural and environmental issues), *Australia's Long-Term Emissions Reduction Plan* (Emissions Reduction), the *National Hydrogen Strategy*[22], the *Technology Investment Roadmap*[23], the *Future Fuels and Vehicles Strategy*[24], the annual *Low Emissions Technology Statements*[25] and the *National Climate Resilience and Adaptation Strategy*.

Additional benefits include:

- enabling Australia to meet its 2030 Emission Reduction Target of 26–28 per cent below 2005 levels by 2030[26]
- low emissions technologies could provide new export revenue for Australia of over $30 billion annually[27]
- a circular economy has the potential to generate 17,000 jobs and add $210 billion to GDP by 2047–48[28].

Researchers can support the transition to a net zero economy through a broad range of activities. For example, both basic and translational impact in renewable technology development can lead to innovations such as novel fuel production. Innovative energy storage solutions are especially important in translational research for scale-up and prototyping.

Achieving a net zero economy also requires consideration of the human dimensions of the transition. Successful transition will rely on societal buy-in and behavioural change, facilitated by government policies and initiatives. Research infrastructure to enable relevant policy research includes access to novel large-scale, longitudinal datasets and complex software models, drawing on heterogeneous data sources and supported by appropriate expertise.

22 Department of Industry, Science, Energy and Resources, ***Australia's National Hydrogen Strategy***, Australian Government, 2019.

23 Department of Industry, Science, Energy and Resources, ***Technology Investment Roadmap***, Australian Government, 2020.

24 Department of Industry, Science, Energy and Resources, ***Future Fuels and Vehicles Strategy***, Australian Government, 2021.

25 Department of Industry, Science, Energy and Resources, ***The Low Emissions Technology Statement 2021***, Australian Government, 2021.

26 Prime Minister and Cabinet, ***Australia's 2030 Emission Reduction Target***, Australian Government, 2015.

27 Department of Industry, Science, Energy and Resources, ***Technology Investment Roadmap: Low Emissions Technology Statement 2021***, Australian Government, 2021.

28 KPMG Economics, ***Potential economic pay-off of a circular economy***, April 2020.

Image credit: istock

Research to support transitioning to a net zero economy should be underpinned by the following research infrastructure:

- Advanced renewable and other zero emissions technology development facilities
  - Renewable and zero emissions technology development facilities, include prototyping and pilot testing equipment to aid in the scale-up of zero emission technologies.
- Hydrogen energy development and storage testing facilities
  - Hydrogen development facilities include support to develop existing and next generation hydrogen electrolysis technologies, catalysts and liquefaction techniques, as well support to develop downstream processing equipment. Hydrogen storage facilities would allow research on different hydrogen forms (e.g. liquid hydrogen and ammonia).
- Publicly accessible national energy database
  - A publicly accessible national energy database comprises open access, integrated and deidentified datasets on consumer energy consumption from the Australian Energy Market Operator and Distributed Network Service Providers.

Image credit: Pixabay

3.5 Defence

Challenge: Defence exports are growing, with a focus on increasing the international competitiveness and success of Australian defence industry. The sector provides advanced technology with cross-sectoral applications and delivers on our national security imperatives as outlined in the Defence Industrial Capability Plan.

In a complex global system, Australia must maintain its defences against external threats and support sovereign capability development across key sectors and supply chains. This is a multilayered endeavour which addresses issues in cybersecurity, materials development and defence technologies and underpins national security.

Addressing this challenge aligns with government priority frameworks, including the *2020 Defence Strategic Outlook*, *2020 Force Structure Plan*, the *Modern Manufacturing Strategy* (Defence), the *Blueprint for Critical Technologies* (risk of increased cybersecurity threats), the *Defence Science and Technology Strategy 2030*[29], *National Security, Science and Technology Priorities*[30], the *Defence White Paper*[31], the *Defence Industrial Capability Plan*[32] and the *Sovereign Industrial Capability Priorities*.

Addressing this challenge has the additional benefits of:

- further bolstering Australia's defence industry potential for job creation and economic growth
- ensuring a safe digital environment for Australia
- supporting Australian industries in entering some of the world's most advanced global supply chains.

Researchers have an important role in supporting development of highly secure and resilient communications and data systems to support Australia's national security. This includes developing the new technologies that will ensure the integrity of key services across the government, defence, business, transport, emergency and health sectors, as well as contributing to enhanced defence operational capability or strategic advantage and the growth of sovereign industry capability. Research also improves our understanding of the vulnerabilities, threats and impacts of cyberattacks, which influence the development of new technologies and software applications to protect Australia's critical infrastructure.

Research to support Australian defence should be underpinned by the following research infrastructure:

- Cybersecurity data ecosystem coordination, encryption technology
  - Cybersecurity infrastructure supports highly secure and resilient software applications, communications and data management, as well as new technologies and approaches to support understanding of cybersecurity environment and impacts.
- Defence materials, components and equipment development
  - Sovereign defence R&D and manufacturing, including development and integration of emerging technologies, testing and prototyping, scale-up manufacturing of products and components supporting Australian defence priorities.

29 Department of Defence, ***Defence Science and Technology Strategy 2030***, Australian Government, 2020.

30 Department of Defence, ***National Security Science and Technology Priorities***, Australian Government, 2020.

31 Department of Defence, ***2016 Defence White Paper***, Australian Government, 2016.

32 Department of Defence, ***Defence Industrial Capability Plan***, Australian Government, 2020.

3.6 Space

Challenge: Space technologies enable activity across the economy. Our emerging global position is underpinned by research expertise, geographical location, cutting-edge facilities and advanced manufacturing capabilities.

The global space sector is growing rapidly, with smaller space technologies and cheaper access to space driving faster innovation. The space sector touches many areas of the Australian economy and society, from communications and positioning to weather forecasting and emergency management. Australia's geographic location, expertise in robotics, sensors and automation, as well as expertise in space technologies such as advanced communications, quantum technologies, rocket propulsion, space medicine and astronomy create the conditions for significant transformation and growth in the sector.

The Space challenge aligns with government priorities, including the *Modern Manufacturing Strategy* (Space), the *Science and Research Priorities*, the *National Climate Resilience and Adaptation Strategy*, the *National Security, Science and Technology Priorities*, the *Blueprint for Critical Technologies*, *Australia's Long-Term Emissions Reduction Plan*, the *Defence Science and Technology Strategy* and the *Australian Civil Space Strategy*.

Addressing this challenge has the additional benefits of:

- the potential to generate additional 20,000 jobs by 2030 while growing the sector from approximately $5 billion to $12 billion[33]
- direct dependencies on Earth observation data contribute more than $3.3 billion per annum to GDP, and the field shows strong potential for continued growth[34]
- augmenting the *Australian Civil Space Strategy* ambition of stimulating more than $1 billion of capital investment in Australia's civil space industry by 2028[35].

The government has long supported astronomy R&D and Australian astronomy research leads the world. Researchers advance space and astronomy knowledge through a broad range of activities. The detection and analysis of information carried by gravitational waves provides astronomers and the wider scientific community access to previously unknown understandings of the universe, which advances physics, astronomy and astrophysics. Materials science research also supports the development of innovative products to launch into orbit to improve Australia's sovereign space capabilities.

33 Australian Space Agency, ***Advancing Space: Australian Civil Space Strategy 2019-2028***, Australian Government, 2020.

34 ***CSIRO Earth Observation Data***, Australian Government 2021.

35 Australian Space Agency, ***Advancing Space: Australian Civil Space Strategy 2019-2028***, Australian Government, 2020.

Research to advance space technology and astronomy research should be underpinned by the following research infrastructure:

- Earth observation infrastructure
  - Earth observation (EO) infrastructure includes EO missions and payloads, associated ground systems, EO data quality assurance and integrity monitoring (including ground calibration), *in situ* sensor networks, EO data access (including radio frequency and optical ground stations) and EO data management, storage and access provision.
- Space exploration
  - Space exploration includes infrastructure to support launch vehicle development and launch infrastructure, life support systems, optical deep space communications, space medicine and life sciences, development, test and qualification facilities for space-based robotics (including analogue sites) and space monitoring (space situational awareness and space weather).
- Optical and radio astronomy infrastructure and data storage
  - Optical and radio astronomy infrastructure includes both domestic infrastructure and participation in international projects such as the Square Kilometre Array and the European Southern Observatory. It also includes large-scale data storage.
- Astronomy precision measurement infrastructure
  - Astronomy precision measurement infrastructure includes the Laser Interferometer Gravitational-Wave Observatory (LIGO) and related high-sensitivity instruments, for enhanced detection of gravitational waves and measurement of the optical field.

The Very Large Telescope (VLT) during observations, located at the Paranal site of the European Southern Observatory (ESO), Chile.
Image credit: ESO/S. Brunier

3.7 Environment and climate

Challenge: Our future prosperity will be safeguarded by positioning Australia to better anticipate, manage and adapt to our changing climate.

Australia faces complex climate and environmental threats that require ongoing management and adaptation to protect its unique ecosystem and environment. Furthermore, Australian prosperity depends on business and industry being prepared to meet growing climate threats. Not responding to climate change could be costly, with modelling predicting losses of $19 billion in reduced agricultural productivity by 2030, $39 billion per year in natural disaster costs by 2050 and over $225 billion in lost assets from sea level rise by 2100[36].

Addressing this challenge aligns with government priority frameworks, including the *Science and Research Priorities* (Environmental Change), the *Modern Manufacturing Strategy*, the *National Agricultural Innovation Agenda*, *Australia's Critical Minerals Strategy 2019* and the *National Climate Resilience and Adaptation Strategy*.

Additional benefits include creating lucrative new industries such as the blue economy (sustainable use of ocean resources for economic growth, improved livelihoods and jobs and ocean ecosystem health) that could be worth up to $68 billion per annum[37].

Researchers help manage environmental and climate threats through a broad range of activities. For example, research into biodiversity conservation is necessary to ensure the protection of Australia's unique species. Research to predict climate change and natural disaster patterns allows for better design and planning of cities, infrastructure and agricultural projects to mitigate and reduce the impact of these threats. Research that focuses on environmental observation improves the understanding of Australia's terrestrial, atmospheric, coastal and ocean environments, including the Southern Ocean and Antarctica.

Research to safeguard future prosperity against environmental and climate threats should be underpinned by the following research infrastructure:

- Biodiversity monitoring, collection and analysis infrastructure
  - Biodiversity monitoring, collection and analysis infrastructure includes collections of species and specimens as baseline infrastructure. These support environmental monitoring and management, biosecurity management, long-term biodiversity monitoring at a national scale and underpin taxonomic data.
- Networked environmental modelling infrastructure
  - Networked environmental modelling communities enable the sharing of data and models across research communities such as that proposed by the NEPS scoping study. NEPS includes a synthesis capability, modelling infrastructure and governance hub.
- Integrated, publicly accessible environmental datasets
  - Integrated publicly accessible environmental datasets include urban, biodiversity, terrestrial, ocean, freshwater, groundwater, estuarine and atmospheric datasets from state and territory monitoring programs and NRI. Additionally, it includes large-scale collections of earth, soil and water samples.

36 Climate Council, ***Compound costs: How climate change is damaging Australia's economy***, 2019.

37 Australian Institute of Marine Science, ***The Aims Index of Marine Industry: December 2018***, Australian Government, 2018.

- Marine, coastal, freshwater, groundwater and atmospheric monitoring and observation infrastructure
  - Includes infrastructure for sea floor mapping (vehicles), observation and monitoring of Australia's coastal, estuarine, freshwater and groundwater environments, the Southern Ocean and atmospheric measurement.
- Climate modelling and adaptation infrastructure
  - Climate modelling and adaptation infrastructure includes software to develop sophisticated models to predict climate trends, climate monitoring technology, (e.g. radar equipment to capture high resolution precipitation data, expanded network monitoring flux stations for increased ecosystem data collection) and open-source climate adaptation datasets.

Voyage Chief Scientist, Dr Elizabeth Shadwick, checks an IMOS deep-water mooring surface float on CSIRO research vessel *Investigator*.
Image credit: CSIRO/Ben Arthur.

3.8 Frontier technologies and modern manufacturing

Challenge: Developing and translating critical technologies required to support modern manufacturing and secure supply chains. Success will include investment in research and commercialisation of critical technologies.

An Australian modern manufacturing sector that is based on innovative, high value-add industries will be critical to fostering a prosperous modern economy. To accomplish this, Australia will need to capitalise on its comparative advantages and develop select critical technologies that will add value to existing manufacturing, create new disruptive industries, unlock new export opportunities and enhance sovereign manufacturing capability. This will enable Australia to be recognised as a high-quality and sustainable manufacturing nation that helps to deliver a strong, modern and resilient economy for all Australians.

This challenge aligns with government priority frameworks, including the *Modern Manufacturing Strategy*, the *Science and Research Priorities* (Advanced Manufacturing), the *Australian Medical Research and Innovation Priorities*, the *Australian Civil Space Strategy*, the *Sovereign Industrial Capability Priorities*, the *Defence Science and Technology Strategy* and the *Blueprint for Critical Technologies*.

Addressing this challenge has the additional benefits of:

- ensuring ongoing basic research excellence
- supporting innovation and investment
- maximising social and economic impact from research discoveries.

Frontier technologies and modern manufacturing encompass a broad range of activities, including the translation of research outcomes into socially beneficial and marketable products and services, and the commercialisation of public sector research. For example, research into novel technologies for advanced manufacturing can:

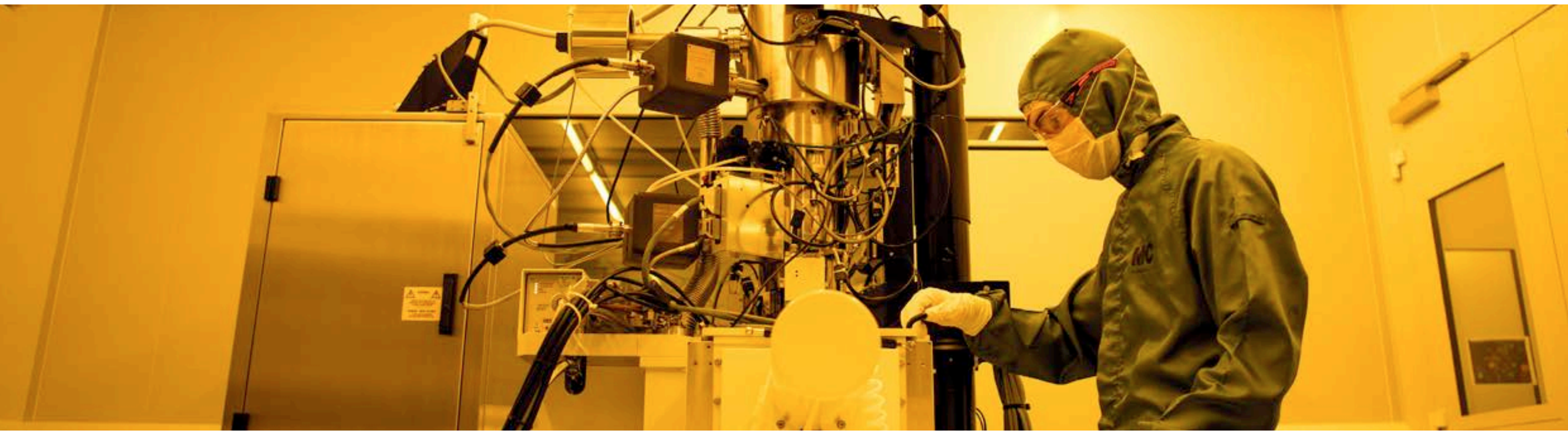
- deliver products with superior and customised attributes
- improve efficiencies across production floors and value chains
- aid real-time monitoring and data-driven decision-making.

In addition, social science research and research into user experience and human-centred design can help develop trust and adoption of novel technologies (such as AI/ML) and products (such as biomanufactured sustainable alternative food products).

The line between research areas and research infrastructure is less distinct for this challenge. There is a continuum on which researchers undertake research to further technology developments and use technology as infrastructure to aid further research and discovery. Research into frontier technologies and modern manufacturing should be underpinned by the following research infrastructure:

- Robotics infrastructure
  - Robotics infrastructure assists with tasks that are complex, high precision, repetitive or hazardous. As this technology develops, assistive robots that work collaboratively with humans will improve sensing, awareness and decision-making capabilities that allow full autonomy and self-learning behaviour.
- Nanofabrication infrastructure
  - Nanofabrication infrastructure includes capabilities for lithography, etching, deposition and metrology. These address specific product limitations such as durability, weight, look and feel, and novel attributes such as biocompatibility, biodegradability and energy efficiency.

- Space-related manufacturing infrastructure
  - Space-related manufacturing infrastructure supports upgrading existing facilities and developing new facilities to manufacture and integrate complex spaceborne components and systems, and to increase global value chain integration, including infrastructure for space payload test and qualification.
- Quantum technologies infrastructure
  - Quantum technology infrastructure supports quantum device design, engineering and fabrication, precision electronics, optics, software development, materials and metrology. This includes rapid prototyping infrastructure for quantum sensors, cryogenics equipment for testing and measurement, fabrication facilities for quantum technology components (such as quantum computing hardware) and training and development tools.
- Synthetic biology infrastructure
  - Synthetic biology infrastructure supports research, development and manufacturing of novel products. This includes biofoundries to rapidly assemble and test DNA constructs, facilities to manufacture synthetic DNA, DNA sequence repositories and fermentation facilities to scale-up and test manufacturing of synthetic biology products.
- Omics facilities
  - Omics facilities analyse molecular components of cells (DNA, RNA, proteins and metabolites) in biological samples. This includes equipment (sequencers, mass spectrometers) to characterise biological molecules and bioinformatics personnel and computers to analyse omics data.
- Microscopy and advanced imaging facilities
  - Microscopy and advanced imaging facilities include transmission and scanning electron microscopes and X-ray photoelectron spectroscopes to characterise biological and non-biological materials. Microscopy provides vital support to the fabrication and characterisation of high-tech materials and devices for testing and prototyping. Advanced human imaging facilities (such as magnetic resonance imaging, positron emission tomography and computed tomography scanners) are essential components in a wide array of preclinical and clinical studies. Additionally, they represent fundamental research technology for understanding the effect of pandemics and unique environmental events (e.g. floods and bushfires) on the human body. Imaging platforms are also applied to a broad variety of industrial, research problems including chemical processes, materials science, security, palaeontology and cultural preservation.
- Support for user experience and human-centred design
  - Human-centred design ensures technology is designed from the outset with regard to the human perspective. Social licence research is integral to the uptake and trust of new technologies and will require access to datasets and expertise.



Electron beam lithography (EBL) can build structures that measure just 7 nanometres across. Access to capabilities like EBL is essential to produce new nanotechnologies. Image credit: Melbourne Centre for Nanofabrication

Two scientists at Therapeutic Innovation Australia's National Biologics Facility Victoria Node are gowned up in accordance with good manufacturing practice requirements. Image credit: CSIRO, Merinda McMahon

CASE STUDY

Taking a challenge approach to solving real-world problems

Around the world varied, complex and interconnected global challenges are increasingly being tackled through mission- and challenge-oriented approaches. These approaches deliberately focus multidisciplinary and multisectoral research efforts on real-world problems, such as:

- the US National Science Foundation 10 Big Ideas program, which aims to catalyse cutting-edge research and collaboration across the public and private sectors
- New Zealand's 11 National Science Challenges to focus science investment on topics that matter to New Zealanders
- the Global Research Council (the heads of international science and engineering funding agencies) developing a Statement of Principles for mission-oriented research[38] at the country and global level in May 2021. Missions encompass both curiosity-driven science and strategic research focused on outcomes, and integrate capacities from a broad range of stakeholders, disciplines and sectors.

Through the Global Challenges Research Fund (GCRF), the UK is investing in cutting-edge research to address six global challenges faced by developing countries and address the United Nations Sustainable Development Goals. It is a five-year, £1.5 billion interdisciplinary program that seeks to maximise the impact of research and innovation to improve lives and opportunities in the developing world.

Researchers from the UK work with partners in developing nations and form diverse, interdisciplinary teams. For example, within the cities and sustainable infrastructure challenge, teams study the connections between global temperature rises, heat waves and vulnerability, and are comprised of anthropologists, urban planners, geographers, science and technology experts, architects and engineers.

The first five-year phase of the program has resulted in thousands of researchers from more than one hundred countries working on projects that range from a global network addressing neglected tropical diseases, to the use of groundwater to build community resilience in Nigeria. All research is co-developed with the partner countries to build and embed skills and knowledge.

A 2017 evaluation of the GCRF[39] showed that after only two years, the program had begun to transform traditional models of public research funding, particularly through the promotion of interdisciplinary work on complex development challenges, such as non-communicable diseases. Approximately 80 per cent of lead institutions and partner organisations agreed that the GCRF was likely to help UK science take a lead role in addressing the most important development challenges.

38 Global Research Council, ***Statement of Principles on Mission Oriented Research***, 2020/21.

39 Independent Commission for Aid Impact, ***Report: Global Challenges Research Fund***, 2017.

3.9 Current NRI support for research challenges

Table 1 demonstrates that current NRI is well positioned to support research in addressing the eight NRI Roadmap themes and challenges.

As an example, consider *Challenge 3.6: Space*, which will require a multidisciplinary approach:

- the National Computational Infrastructure and Pawsey Supercomputing Centre run complex modelling and simulations
- the creation, analysis and retention of associated data assets is supported by the Australian Research Data Commons
- Astronomy Australia Limited facilitates access to world-leading research infrastructure for Australian astronomers
- accelerators such as those at Heavy Ion Accelerators and the Centre for Accelerator Science are used in the design and development of advanced materials for the manufacture of space products and services
- Microscopy Australia can characterise the structure, composition and chemistry of materials
- the Terrestrial Ecosystem Research Network and AuScope have capabilities in the development and deployment of satellites.

Table 1. Mapping of challenges against current NCRIS projects*

NCRIS facility	Resources Technology and Critical Minerals Processing	Food and Beverage	Medical Products	Recycling and Clean Energy	Defence	Space	Environment and Climate	Frontier Technologies and Modern Manufacturing
AAL					■	■		■
ACDP		■	■		■		■	■
ACNS	■	■	■	■	■	■	■	■
ALA		■					■	■
ANFF			■	■	■	■		■
APPF		■	■			■	■	■
ARDC	■	■	■	■	■	■	■	■
AURIN			■	■			■	■
AuScope	■			■		■	■	■
BPA		■	■	■	■	■	■	■
CAS	■	■	■	■	■	■	■	■
EMBL (Aus)		■	■				■	■
HIA	■	■	■	■	■	■	■	■
IMOS		■		■	■	■	■	■
MicroAu	■	■	■	■	■	■	■	■
MNF	■	■					■	■
NCI	■	■	■	■	■	■	■	■
NDF	■	■	■	■			■	■
NIF	■	■	■				■	■
PA		■	■				■	■
Pawsey	■	■	■	■	■	■	■	■
PHRN			■				■	■
TERN		■		■		■	■	■
TIA			■		■		■	■

* Note: Pilots supported through the 2020 Investment Plan such as ACCESS-NRI, HASS RDC and synthetic biology (biofoundry) have not been included in Table 1.

Gravitational Wave Data Centre (GWDC) Program Lead, Jarrod Hurley, with the OzSTAR Supercomputer, located at Swinburne University of Technology. Image credit: Carl Knox, ARC Centre of Excellence for Gravitational Wave Discovery, Swinburne University of Technology.

4

Opportunities for system-wide enhancements in NRI

> The Roadmap consultation process highlighted the strongly cross-cutting nature of NRI and helped identify gaps and opportunities that are relevant to the NRI system. These issues and opportunities are the focus of this chapter, raising possible areas for government investment and are relevant to supporting the step-changes identified in *Chapter 6: Potential for step-change*.

4.1 Continental-scale observations

Observations at continental-scale produce and continually update datasets of national significance that are beyond the capacity of individual researchers to collect. They allow researchers to identify national and global trends and understand terrestrial ecosystems, biodiversity, geology, oceans, coasts, climate and atmosphere, and how they are changing. This helps protect our infrastructure, industries and natural heritage, while providing information products and services for government, defence, industry and the general public.

Consultations for the 2021 Roadmap highlighted gaps in our continental-scale observational capability. There is a need for increased observational capacity in coastal zones and on the ocean floor, with better integration of marine, freshwater, groundwater and terrestrial monitoring. Coordination of marine monitoring infrastructure (such as the approach taken by Australia's coastal vessel fleet to collect and deliver observations) is critical for the accurate forecasting and modelling that underpin industry operations and the growth of Australia's blue economy. There is a need for greater capacity in atmospheric and air quality monitoring in both regional and urban areas. There is also significant potential for enhanced marine and terrestrial biodiversity and biosecurity monitoring infrastructure that can identify the DNA of animals and microbes from soil and water samples. The requirement for wide spatial coverage, in addition to working in remote and challenging locations, makes the benefits of well-integrated continental observation infrastructure significant.

Increasingly, satellite data is being used in a wide range of observational applications, complementing ground-based and autonomous (e.g. drone) sensor networks. Earth observation capacity requires timely high resolution satellite images, ground-based calibration stations and the expertise and software tools to produce datasets. Better coordination of satellite and ground-based observational infrastructure would allow for the collection of richer datasets.

It is evident that new capability in continental-scale observations will contribute towards many of the challenges outlined in *Chapter 3: Research themes, challenges and NRI impact*. Doing so in a coordinated way, with shared observational capability across NRI and for different research domains, will help improve interconnections and drive efficiency. Alignment and compatibility with international efforts in observation and monitoring will ensure most value. As further discussed in *Chapter 6: Potential for step-change*, a step-change in the scale and integration of these NRI will be critical in informing Australia's adaptation strategy to environmental and climate threats.

A unique drone's view of one of several Terrestrial Ecosystem Research Network environmental monitoring field stations captured by a team of researchers utilising the site's NCRIS-enabled infrastructure. Image credit: Lenny Hambrecht and Darren Turner

4.2 Large-scale integrated datasets

Strategic national data collections require an intentional approach and a governance framework appropriate for that purpose. Open access to data will also provide many opportunities to support data-driven science.

The government is exploring how to safely and securely leverage large-scale Australian datasets to support national and international collaboration. This will generate additional value from government and publicly funded data resources. Examples of such national-scale datasets include those used for health, environmental applications, geo-mapping and agriculture, the understanding of human and societal behaviours, public policy, public service delivery and smart urban design.

Integration of large datasets could provide comprehensive national-scale information sources for researchers. Development and maintenance of these integrated datasets requires infrastructure that provides access, and applies standards, across the collection to allow for data interoperability. Interoperability of data is essential to ensure use and reuse of data and collections to minimise duplication of efforts and resources. Well-integrated datasets facilitate and encourage interdisciplinary approaches to problems and allow linking of sectors (e.g. integrated climate, public health and built infrastructure data to assess social impacts of environmental change). In this way, access to large-scale integrated datasets can support researchers across all challenges discussed in *Chapter 3: Research themes, challenges and NRI impact*.

With the rapidly increasing amounts of data generated, increasing data storage capacity is needed as a national research asset, especially for long-term preservation. Researchers may want to use data in 30 years and need certainty that they will be able to do so. Preservation standards, storage architectures and interoperability all need to be considered for any data storage solutions (such as data repositories).

Addressing the issues of data storage and creation of interoperable national-scale datasets will be considered as part of the proposed NDRI Strategy discussed in *Chapter 5: Building on a strong NRI foundation*. The Australian Government is already taking steps to improve its data systems though initiatives such as the *Australian Data Strategy*[40].

40 Department of the Prime Minister and Cabinet, ***Australian Data Strategy***, Australian Government, 2021.

4.3 Physical collections and biobanking

Physical collections are a vital resource for research and underpin activities that range from health and medical research to ecology and agriculture. Physical collections of specimens and taxonomy are also critical to support the identification of biosecurity risks and determine action, supporting Australia's environmental and climate adaptation strategy (*Chapter 6: Potential for step-change*).

Metadata capture of physical collections is essential to ensure specimens are findable and accessible to researchers. Metadata standards are also necessary for data to be interoperable across institutions and platforms and to address current disparity in discoverability, accessibility and quality of data. Evolving analytical technologies are also generating new opportunities for specimen and sample use and reuse.

Biodiversity and environmental sample biobanks have significant potential as baseline infrastructure to support environmental monitoring and management, biosecurity, biodiscovery and bioprospecting. The value of current biological and environmental sample collections could be improved by creating an open access infrastructure. This would involve the development of unified sample management systems, metadata protocols, consistent access models and shared data infrastructure. Rapidly evolving analytical technologies (genomics, imaging, digitisation etc.) are generating new opportunities for specimen and sample use and reuse that have not been previously possible.

These technologies can also help manage the finite resources of biobanks. Application of new technology means old samples are becoming valuable in new ways across new domains, and can assist researchers in addressing the challenges outlined in *Chapter 3: Research themes, challenges and NRI impact*.

Australia also has a range of high-quality biobanks that are immensely valuable to biomedical and clinical research and provide important information for synthetic biology research. Medical and human biobanks are currently implemented at the state and territory level but are not coordinated or integrated and involve complex ethics and regulatory frameworks.

The Atlas of Living Australia harmonises biodiversity data from biological collections, research organisations, government, industry and citizen science groups. Image credit: Australian National Insect Collection, CSIRO

Roadmap consultations highlighted the need for a skilled workforce and expertise to support physical collections and biobanking. While researchers are adept at collection, there are skills gaps in the curation and preservation of collections.

Infrastructure for the collection and curation of research objects is also vital for HASS. These research objects can include surveys collected through fieldwork, textual materials (such as legal cases and judgements) as well as objects in museums and galleries. These collections, along with their digital counterparts, represent the equivalent of instrumentation-based facilities used in other research domains. They need similar levels of specialists and expertise to support research activities through curating historical artefacts, navigating licensing conditions and managing the complexities of secure access.

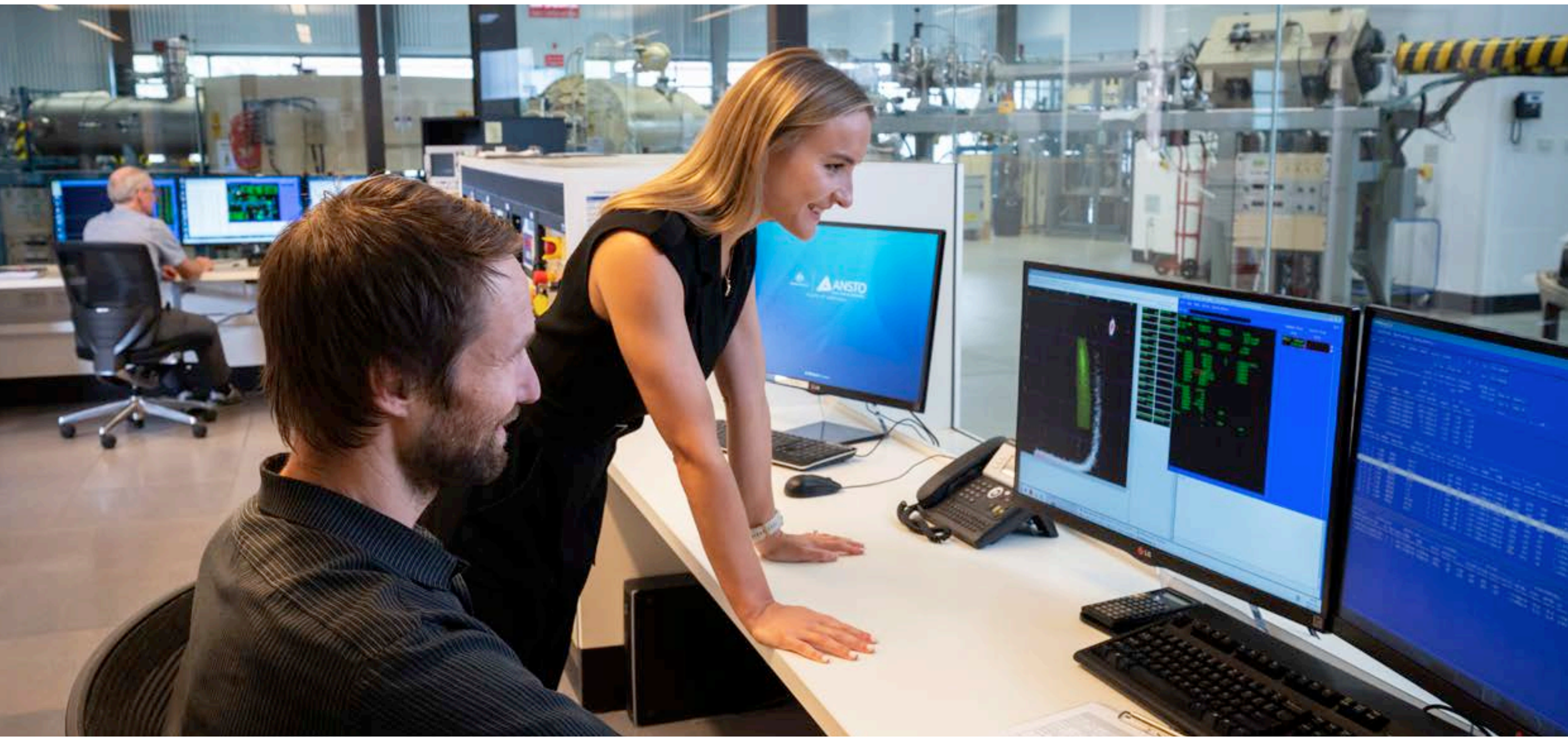
A national approach to managing Australia's diverse collections would make certain that specimens are accessible, findable and usable to ensure the greatest benefit, as discussed further in *Chapter 6: Potential for step-change*.

4.4 Software analysis tools and platforms

As datasets become larger and more complex, the tools that are available to researchers also need to be more sophisticated and able to span multiple domains and scales (e.g. environmental prediction utilising agricultural and built environment data). Tools such as AI/ML and complex visualisation techniques are becoming widely adopted and are used across different sectors to analyse data. Improving researcher training and access to such tools will enable better analysis and utilisation of large-scale datasets, such as those from social media, health, agricultural and environmental databases.

Consultation identified the opportunity to develop more 'research data commons'. These initiatives are large, coordinated and optimised to address broad science and research priorities. Data commons provide shared and reusable analytics platforms, software and data, all tailored for specific communities. They are developed collaboratively with researchers and NRI. Existing data commons include the EcoCommons and BioCommons, and the HASS Research Data Commons is in development. These shared platforms help lower costs, improve efficiency and reduce duplication of effort across NRI and its user communities. They also augment existing research infrastructure and provide technical, social and governance foundations for potential new research infrastructure (such as a NEPS).

Developing a more coordinated national capability around research training and access to new digital tools could allow researchers to analyse results and collaborate more efficiently to address the full range of challenges (*Chapter 3: Research themes, challenges and NRI impact*) and underpin step-changes (*Chapter 6: Potential for step-change*). The NDRI Strategy discussed in *Chapter 5: Building on a strong NRI foundation* could also support this outcome.



Inside the SIRIUS 6 megavolt accelerator and VEGA 1 megavolt accelerator control room at ANSTO's Centre for Accelerator Science (CAS). VEGA and SIRIUS are two of the four megavolt accelerators at CAS supporting a wide range of research and industry users through ultra-sensitive analysis and precision irradiation. Image credit: Australian Nuclear Science and Technology Organisation

4.5 Bridging innovation gaps with translation NRI

Research translation into real-world outputs occurs at many levels, such as the development of commercial products, improved decision-making and policy, risk management (e.g. bushfires) and public health outcomes. These outputs provide a wide array of benefits to end users, such as government, industry, health services and community groups. NRI supports translation and end user engagement in many ways, including through the provision of the tools necessary for the delivery of high-quality research outputs.

Commercialisation of research is one form of translation that can yield important economic returns and lead to the creation of new businesses and jobs. In 2020, Australian research organisations generated $242 million in commercialisation revenue and 54 new spin-out companies and start-ups[41]. To maximise social and economic dividends from the research sector, it is critical that NRI supports a broad range of research activities across the entire innovation chain.

In the development of commercial research outputs, technology readiness levels beyond proof-of-concept frequently lie outside the remit of the university research sector. At the same time, the private sector is often reluctant to invest in unproven technologies. Roadmap consultations highlighted this gap as a key limitation, impeding translation of promising Australian research into impactful, real-world interventions. Translation NRI can play a critical role in bridging the gap between discovery research and the point of value inflection, beyond which industrial support becomes available.

Development of frontier technologies will be critical in supporting emerging new Australian industries and a strong advanced manufacturing sector. Access to applied engineering infrastructure that supports prototyping and early validation will help ensure a steady flow of innovative technologies. Prototyping capability at the NRI level for new materials, components and devices (particularly those produced through nano- and micro-fabrication) will enable the translation of value-added research products with wide-reaching applications, such as precision sensors, advanced materials and quantum technologies. Fabrication must be guided by measurement capabilities at a level of precision that aligns with international quality management systems.

A complementary need is for scale-up of production processes to supply early testing (such as Phase I clinical trials), test beds or demonstration (e.g. manufacturability of minimum viable products). This may vary by application, but NRI-level facilities could aim to be configurable to different process workflows and regulatory requirements and should encompass the translation expertise necessary to support researchers in technology demonstration.

Driving impact from research discovery is wide-reaching and can help address all challenges outlined in *Chapter 3: Research themes, challenges and NRI impact*. However, it will be particularly critical in exploiting frontier technologies and their translation into new manufacturing sectors. For example, synthetic biology researchers will require significant and varied fermentation scale-up capability and expertise to enable translation of products.

Importantly, translation NRI must be openly accessible infrastructure that provides both researchers and innovators (such as small to medium enterprises) affordable access to equipment, expertise and the advice necessary to support testing and validation. Addressing this important gap in the Australian research sector would be a game-changer in driving value from Australian research excellence and ingenuity, as discussed further in *Chapter 6: Potential for step-change*.

41 Knowledge Commercialisation Australasia, ***Survey of Commercialisation Outcomes from Public Research (SCOPR)-2020 Report***, 2021.

5

Building on a strong NRI foundation

The 2021 Roadmap development process affirmed that Australia possesses a modern NRI system that is well-positioned to support researchers in addressing current and emerging major challenges. However, consultation also identified targeted changes that could drive higher levels of impact through:

- improved governance structures and workforce planning
- increased access and engagement with industry
- an increased user-centric focus
- an integrated data and computing ecosystem.

These issues are discussed below and could support the step-change NRI investment identified in Chapter 6: Potential for step-change.

5.1 NRI governance

Recommendation 4: Establish an Expert NRI Advisory Group to drive a more effective NRI ecosystem

Government needs ongoing independent, long-term strategic advice on NRI priorities, trends and opportunities. This is best achieved through the establishment of an expert advisory group with a relevant range of skills. This should be established within the next six months.

The immediate priorities for the Expert NRI Advisory Group will be:

- development of a NRI Workforce Strategy to support career pathways, address technical skills shortages and identify capability gaps. NRI is underpinned by a highly skilled and increasingly specialised workforce that needs job security and opportunities for career mobility and professional development.
- a review of current NRI facilities and services to identify opportunities for greater integration and alignment of functions across the network. This should include an assessment of impact to inform the investment levels required in each NRI facility, their levels of maturity and identify areas of consolidation. It should examine current business models to ensure NRI is continuing to meet the needs of users and deliver the most impact.
- providing advice to government on immediate and long-term NRI planning and funding strategies. This includes guidance on the most effective way to support government research priorities and maximise NRI co-investment opportunities. Advice should take into account all research income (Australian and State and Territory Governments, industry and the research sector) and where the most impact can be delivered.

NRI governance has been raised in previous Roadmaps and reviews. The need for an Expert NRI Advisory Group was confirmed again in 2021 consultations and is widely viewed by all sectors as an urgent and critically important facet of a modern NRI ecosystem.

To maintain Australia's strong NRI network, more needs to be done to protect current and future investments. Major national events such as the 2019–20 bushfires and global pandemic have emphasised the need for strategic long-term planning to build Australia's sovereign capability and ensure critical supply chains. The Australian Government is currently working with the NCRIS projects to ensure the University Foreign Interference Taskforce guidelines[42] are applied to the research they support, as well as build a framework that is consistent across the various research organisations that use NCRIS infrastructure.

The 2015 Research Infrastructure Review[43] found that although multiple government departments and agencies played a role, there was no single body providing overall strategic direction for NRI investment.

An independent Expert NRI Advisory Group would provide timely direction to maintain NRI that is flexible, relevant and responsive to emerging trends, opportunities and challenges. It would bring together experts with the appropriate skills and knowledge across the innovation system to guide long-term decision-making and provide continuity in NRI investment. This would offer more strategic, regular and agile planning aligned to national priorities and emerging research needs.

The establishment of a cohesive overarching governance framework would also facilitate opportunities to drive greater integration, coordination and optimisation of the Australian NRI network. This would include the development of targeted, coordinated workforce approaches across the NRI network to address career pathways and technical skills shortages. The group would also be responsible for reviewing the NRI Principles and guiding future Roadmap processes.

An overarching governance framework would provide benefits across the various layers of the NRI ecosystem and drive changes across national, program and project levels:

- national: guiding strategic decision-making and providing advice to government
- program: driving opportunities for integration and improved efficiency, addressing skills and career pathways, and improving access, awareness and industry engagement
- project: ensuring boards and senior staff have the appropriate skills to effectively contribute to strategic planning and drive improved program level outcomes, such as research translation.

42 Department of Education, Skills and Employment, ***Guidelines to Counter Foreign Interference in the Australian University Sector***, Australian Government, 2021.

43 PM Clark, I Chubb, A Finkel and O Mayo, ***Research Infrastructure Review Final Report September 2015***, Department of Education and Training, Australian Government, 2015.

5.2 Skills and workforce planning

One of the immediate priorities for the Expert NRI Advisory Group should be the development of an NRI Workforce Strategy. People and expertise are an intrinsic and essential part of NRI, and include specialists, scientists and engineers from a wide array of disciplines. NRI staff manage, maintain, optimise and operate facilities, but also provide critical expert advice to develop research infrastructure, support NRI users and provide field-specific training. Due to the cross-cutting nature of NRI, staff play an important role in supporting collaboration, including industry engagement and raising awareness of NRI capabilities. This highly skilled workforce is needed to maximise the benefits of existing NRI investments, new technologies and applications. The continual training and development of skilled staff is important to provide technical support to the research community.

Human capital and workforce issues have been identified in previous NRI Roadmaps. Career progression and mobility for NRI staff within the sector is often limited due to their specialised skills, particularly as their roles typically make traditional academic pathways unavailable. Additionally, career progression is limited by systemic job insecurity caused by short term contracts. Current NCRIS projects provide opportunities for training and professional development, such as staff exchanges, mentoring and participation in conferences. However, these opportunities are not consistent across projects.

The attraction and retention of skilled staff can be challenging. This has resulted in both system-wide skills shortages (research software development, AI) and field-specific skills shortages (accelerator experts, taxonomists). Many of the system-wide shortages concern DRI and reflect shortages faced in the broader research sector. It is also unclear how COVID-19 will affect Australia's workforce planning and opportunities for international collaboration, although the negative impact on the university sector has been significant[44].

A NRI Workforce Strategy could drive coordinated improvements in NRI career pathways and technical skills shortages. The Strategy should consider how staff development is embedded in future NRI investment planning, and how to cultivate sustainable career options for a new generation of NRI staff. Apprenticeships, better recognition of technical staff, improved external and internal training programs and the development of non-pay incentives have been suggested as possible solutions in the UK[45]. Formal qualifications in research infrastructure management could be developed for NRI leadership, similar to the Executive Masters in Management of Research Infrastructures offered by the University of Milano-Bicocca[46]. The development of entrepreneurial or business skills for NRI staff could also be an area of future focus, helping facilitate transitions between the research and commercial sectors. The potential integration of governance and functions across similar NRI could also assist in identifying career development and mobility opportunities.

New infrastructure investment should also aim to help reduce staffing pressures. Enhancements to autonomous and remote operations could allow NRI staff to deliver services more efficiently, while simultaneously lowering barriers to entry and helping develop new research and industry user communities.

Researchers test drones that will be used in both scientific and humanities research applications at Monash University. Image credit: Monash University

44 Rapid Research Information Forum, *Impact of the pandemic on Australia's research workforce*, Australian Government, 2020.

45 UK Research and Innovation, *The UK's research and innovation infrastructure: Landscape Analysis*, United Kingdom, 2019.

46 University of Milano-Bicocca, *Executive Masters in Management of Research Infrastructures*.

CASE STUDY

Recognising value and driving cultural change for technical experts

The important roles of technicians in UK research and innovation are being recognised through the Technician Commitment initiative.

Established in 2017, the Technician Commitment provides research sector-wide support and representation for the technical profession. It aims to create a more positive culture for the technical community, and improve the visibility, recognition, career development and sustainability of technicians within UK higher education and research. With more than 100 signatories and supporter institutions, the Technician Commitment has helped drive cultural change at institutions across the UK.

As signatories of the Technician Commitment, in 2021 UKRI published an associated Action Plan[47] that set out their aims as both a funder and employer to meet their vison of recognising, celebrating and valuing the essential contribution that the diversity of technically skilled people make across the UK research and innovation system. One of UKRI's nine research councils, the UK Science and Technology Facilities Council (STFC), is also a signatory. STFC operates large-scale research facilities in the UK and manages access to major overseas research facilities for UK-based researchers. It signed up to the Technician Commitment to recognise and build on the key role technicians play in maintaining the Council's leading-edge research excellence and driving solutions to technological challenges.

The Technician Commitment has catalysed signatory institutions to establish technician steering groups and technical conference series, update research publication or authorship policies to recognise technicians' contributions, and review career pathways and frameworks. It has unlocked unprecedented investment into research and technical communities, established new apprenticeship programs and training opportunities for technicians, and developed a strong community of practice.

An IMOS deep-water mooring is recovered from the Southern Ocean by RV Investigator, which is operated by the CSIRO Marine National Facility. Image: CSIRO/Max McGuire

A 2021 review of the program[48] found that over all there is excellent evidence of impact and pace of change in visibility and recognition. The pace of change is slower in career development and sustainability, but this is understandable given the short time the program has been in place and the time it takes to change institutional and sectoral practices.

The release in 2021 of the UK's R&D People and Culture Strategy[49] is seen as an important policy to ensure the cultural changes needed to embed the career progression, pathways and sustainability of skills is achieved by the program.

47 UK Research and Innovation, ***Technician Commitment UKRI Action Plan***, 2021.

48 The Technician Commitment, ***Technician Commitment Progress and Impact***, 2021.

49 UK Department for Business, Energy & Industrial Strategy, ***R&D People and Culture Strategy***, 2021.

5.3 Improvements in NRI impact

Another important priority for the Expert NRI Advisory Group is reviewing the structure, impact, access and strategic planning arrangements of existing NRI for opportunities to integrate governance and complementary functions at the project, organisation and strategic levels. Though Roadmap consultations did not identify any pressing issues impairing the impact of NRI, an ongoing advisory group would have the opportunity to identify needs for reform (e.g. through expansion or decommissioning of services) following an independent review process.

Although the existing NRI network is performing well, some facilities are performing more strongly than others. It is vital to better understand the characteristics that underpin this performance and ensure frameworks are in place that support strong governance, effective long-term planning and identify opportunities for consolidation and streamline services for users. It is also important that the impact of government investment is optimised and measured.

The NRI ecosystem has developed to the point that considerable value can be added through greater integration across functions and domains. Opportunities for greater NRI alignment and integration are discussed further in *Chapter 5.5: Greater alignment and integration of NRI functions*. The 2021 Roadmap consultation process identified opportunities for closer integration of existing services and capabilities. These include:

- streamlining of data-centric facilities to improve accessibility
- integration of data analysis software and tools
- amalgamation of environmental monitoring and data collection
- coordination of Tier 1 and 2 HPC capabilities.

The review would seek to identify opportunities for the more seamless provision of generic and specific services and should be conducted as a matter of priority.

The Gadi supercomputer inside the National Computational Infrastructure data hall.
Image credit: National Computational Infrastructure Australia

CASE STUDY

Creating the Australian Research Data Commons

Recognising the increasingly rapid evolution of digital research infrastructure, the 2016 Roadmap recommended the merger of the Australian National Data Service, National eResearch Collaboration Tools and Resources (Nectar) and Research Data Services to form what is now called the Australian Research Data Commons (ARDC).

eResearch demands a coordinated national solution to meet the ever-growing research needs and reduce duplication and fragmentation across sectors and jurisdictions. The intention of the merger was for ARDC to "…establish an integrated data-intensive infrastructure system, incorporating physical infrastructure, polices, data, software, tools and support for researchers." The 2019 merger enables the ARDC to provide strategic solutions across the entire data lifecycle. Additionally, developing solutions using a common approach is more efficient and the commonality facilitates new interdisciplinary research using new integrated data sets.

Significant time, resources and consultation with stakeholders across academia, government and the private sector has been critical to ensure a smooth transition for the thousands of researchers who rely on ARDC's eResearch services. Successfully integrating and evolving eResearch services has allowed ARDC to introduce larger-scale activities through thematic research data commons that focus resources to address national priorities.

ARDC's successful journey, which started in 2014, demonstrates that integration of NCRIS projects in the future must recognise (1) the importance of a dedicated focus group for identifying and catalysing action on sector-wide perspectives, (2) clarity is essential, particularly regarding objectives, and (3) robust, ongoing engagement with all stakeholders is critical to managing issues, maximising benefits and minimising downsides.

Formed in 2018 by merging the Australian National Data Service, National eResearch Collaboration Tools and resources and Research Data Services, the ARDC is accelerating research and innovation by driving excellence in the creation, analysis and retention of high-quality data assets. Image credit: iStock.

5.4 Improvements in NRI planning

The Expert NRI Advisory Group would provide government with ongoing strategic direction to assist long-term NRI planning and identify opportunities for co-investment. NRI is a complex ecosystem with investment terms ranging from five to 15 years, depending on the size and scale of the infrastructure. In addition, multiple stakeholders invest in NRI across the government, university and private sectors. State and territory governments are vital for NRI, as they provide fundamental contributions to NRI operation (e.g. data) and derive significant benefit from NRI investment. There are opportunities to increase the impact of this investment to drive effective long-term planning.

The Expert NRI Advisory Group would provide advice on immediate and long-term NRI planning that aligns with a range of government (Australian, state and territory) research priorities. It would also seek opportunities to maximise the impact of research income provided by governments, industry, research and other sectors in line with the NRI Investment Principles.

The pace and complexity of change in science and research requires a governance framework that supports government to be responsive, plan well and optimise investment. In addition to the challenges associated with COVID-19, NRI will also need to adhere to international standards and best practice, keep up with constantly evolving technologies, environmental threats and meet the rapidly-growing demand for infrastructure services. It is essential that NRI has a clear long-term vision, with enough flexibility to respond to urgent priorities and emerging opportunities.

Image credit: Phenomics Australia

5.5 Greater alignment and integration of NRI functions

Recommendation 5: Drive a more integrated NRI ecosystem

Modern research occurs across disciplinary boundaries to address increasingly complex problems. This requires linkages, interactions and collaboration within and across the NRI system. The future vision of a seamless ecosystem of NRI services for researchers will require an even greater level of collaboration. Considering the NRI ecosystem as a set of functions (outlined below) could draw out opportunities for further collaboration and integration of services:

- observation and monitoring
- computing and modelling
- management of datasets and collections
- fabrication and manufacturing
- measurement and characterisation.

Consideration of current and future NRI by their broad function could help drive greater integration and improve governance and efficiency. This approach could reduce barriers to access, promote seamless NRI services and support strategies for a focused development of the NRI workforce, ultimately leading to improved research outcomes.

NRI functions can be categorised as:

- Observation and monitoring
  - Observation and monitoring instruments allow researchers to remotely study large-scale complex systems and how they change over time. Though observational infrastructure differs in scale and variables of monitoring, researchers can leverage data from multiple infrastructures to gain greater insights.
- Computing and modelling
  - HPC allows researchers to model highly complex systems and perform advanced analysis of vast amounts of data.
- Management of datasets and collections
  - Datasets and collections are vital for all fields of research. Careful curation of (and improvements to) the reliability, interoperability, accessibility and management of datasets and collections is crucial to ensure use and reuse of data.
- Fabrication and manufacturing
  - Prototyping and pilot testing represent critical steps in transforming research ideas into tangible manufacturable products with real-world impact. This infrastructure enables researchers and innovators to translate research outputs and manufacture materials to be used in research.
- Measurement and characterisation
  - Measurement and characterisation methods analyse the properties of individual samples, including subatomic particles, molecules, materials and organisms. A wide variety of measurement and characterisation infrastructure is required to support measurements of different properties and spanning different size and time scales.

Considering NRI in terms of functions could also help guide investment, strengthen the NRI network and drive greater collaboration within and between NRI. It could also support the Expert NRI Advisory Group (Recommendation 4) in providing strategic advice to government. The government could also consider methods of progressing and incentivising this approach to NRI system improvements through NCRIS program management.

CASE STUDY

Working together to improve Australia's drone-enabled research and decision-making

Drones are used for remote sensing (scanning Earth in different ways from above) across a breadth of natural sciences (Earth, environmental) and humanities (archaeology) disciplines. Importantly and uniquely, drones address a critical data gap between ground observation and satellite-based data observations. Drones also deliver near real-time, societally-relevant information that has not previously been available, but that data can be complex and hard to use.

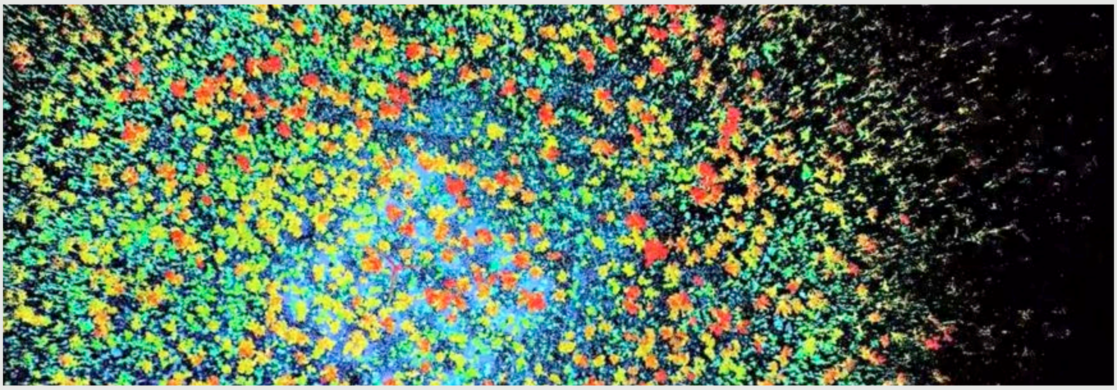
The Australian Scalable Drone Cloud (ASDC) aims to standardise the capture, analysis and translation of scientific drone data for improved access and usability across academia, government and industry. The ASDC is a collaboration between four NCRIS projects (the Australian Research Data Commons, Australian Plant Phenomics Facility, the Terrestrial Ecosystem Research Network and AuScope) alongside Monash University and the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

Established in early 2020, the ASDC is building a cloud-based platform to help researchers manage and analyse drone-collected data. It is establishing best practices in data management (based on findable, accessible, interoperable, reusable (FAIR) data principles) and providing cloud-based analytical and computation capabilities.

In addition, it will enhance partnerships and strengthen networks among several NCRIS projects and research organisations, and foster interdisciplinary relationships between science, engineering, information technology and humanities disciplines that are essential for solving research challenges.

The ASDC will support the use of drone-collected data in research and development at local, state and national levels. In addition to enabling more precise data collection, digital infrastructure improvements (such as cloud-based processing and analytical capabilities) are set to provide near real-time decision support. This will allow authorities to respond better and more quickly to a range of societal and environmental challenges, such as floods and other natural disasters.

The ability to standardise 3D geospatial data gathering, processing and analysis via cloud-based technologies will significantly improve the accessibility, reusability and interoperability of drone data across industry, research and the public sector. This will create a stronger and more reliable tool for the research community that will, in turn, ensure flow-on benefits for the public.



Drone-collected laser scanning data, like these collected by researchers using Terrestrial Ecosystem Research Network's NCRIS-enabled research infrastructure at Litchfield National Park in the Northern Territory, can be used to understand how much carbon an ecosystem stores and how it's changing over time. The drone data and Terrestrial Ecosystem Research Network's permanent monitoring equipment at the site provided the necessary infrastructure to successfully survey these dense tropical forests using drone methods. Image credits: Kim Calders and Terrestrial Ecosystem Research Network.

5.6 Indigenous knowledges and NRI

Indigenous knowledges have great potential to help solve some of our biggest research challenges. The unique laws, languages, cultures, practices, histories and perspectives of Indigenous Australians can strengthen institutions and knowledge systems, enhance the practice, teaching and protection of cultural traditions and guide the development and use of Australian lands and waters.

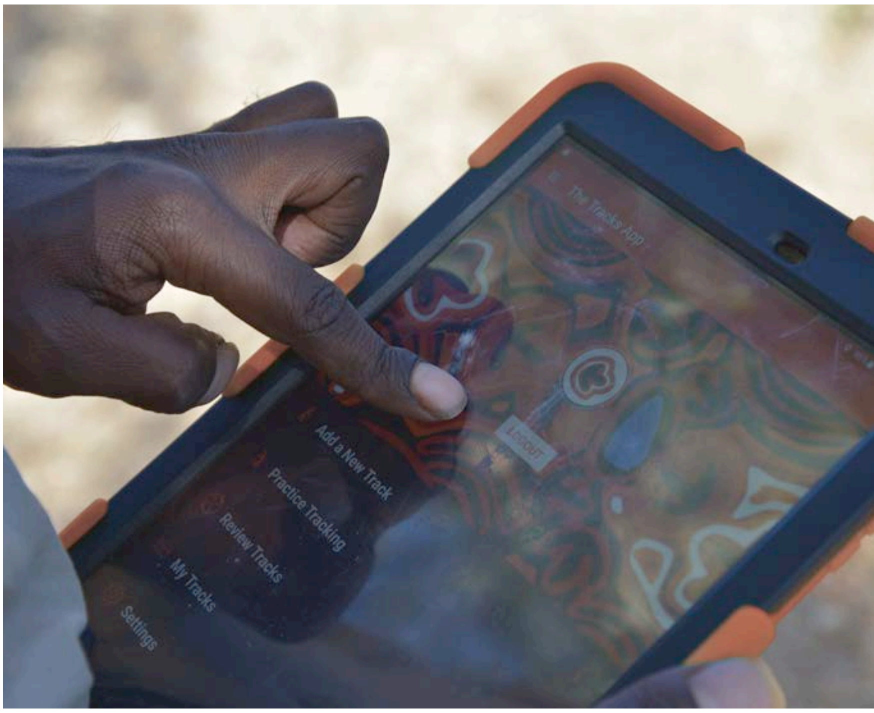
NRI can put research and data in the hands of Aboriginal and Torres Strait Islander peoples pursuing their self-determination aspirations. Aboriginal and Torres Strait Islander peoples' engagement with NRI is ongoing: the 2020 Investment Plan provided funding to the Indigenous Data Network (IDN) to support Indigenous research capability. In partnership with the ARDC and guided by an Indigenous governance arrangement, IDN aims to help Indigenous communities develop skills in data management and resources via technological, training and governance initiatives.

The potential value of NRI for Indigenous communities was also recognised in the establishment of the Indigenous Research Fund, which is supporting the development of the Indigenous Knowledge Exchange Platform by the Australian Institute of Aboriginal and Torres Strait Islander Studies (AIATSIS). The Indigenous Knowledge Exchange Platform will be a gateway to access research and data by, for and about Aboriginal and Torres Strait Islander peoples with strong Indigenous governance. It will also highlight Indigenous-led research and provide a culturally safe place for knowledge (data and evidence) to be stored and shared.

The AIATSIS Code of Ethics for Aboriginal and Torres Strait Islander Research (Code of Ethics)[50] states that "at every stage, Aboriginal and Torres Strait Islander research must be founded on a process of meaningful engagement" and be underpinned by four principles: Indigenous self-determination, Indigenous leadership, Indigenous impact and value and Indigenous sustainability and accountability.

Meaningful engagement between Aboriginal and Torres Strait Islander peoples and NRI must be encouraged and underpinned by these principles. NRI should adopt the AIATSIS Code of Ethics definition of research, which states "all research that impacts on or is of particular significance to Aboriginal and Torres Strait Islander peoples, including the planning, collection, analysis and dissemination of information or knowledge, in any format or medium, which is about, or may affect, Indigenous peoples, either collectively or individually".

There is an opportunity for government to consider an NRI strategy that recognises the value of Indigenous knowledge and encourages Indigenous engagement with NRI. Such a strategy will also contribute to the Closing the Gap initiative[51], particularly Priority Reforms 1, 3 and 4.



Developed by the Central Land Council and the Atlas of Living Australia, the Tracks App supports Indigenous Ranger groups to collect and contribute data to Australia's biodiversity data infrastructure. Image credit: The Central Land Council

50 *AIATSIS Code of Ethics for Aboriginal and Torres Strait Islander Research*.

51 National Indigenous Australians Agency, *National Agreement on Closing the Gap*, Australian Government.

5.7 HASS and NRI

Research in HASS areas is fundamental to understanding people, their interactions with the world and the ways in which their lives, the economy and the environment can be improved through evidence-based interventions. Such research is fundamental and valuable in determining which research questions Australia ought to be asking, and provides frameworks through which we can evaluate the impact of human activity and support the development of policies and practices to address major challenges.

CASE STUDY

Learning the lessons of history

Bushfires are a regular feature of Australian summers, and they are predicted to become more frequent and more severe. The events of the 2019–2020 bushfire season show what was unprecedented is now our future[1].

Emeritus Professor Tom Griffiths is an environmental historian who was the Foundation Director of the Australian National University's Centre for Environmental History when the Black Saturday fires tore through the Yarra Valley in 2009. He had studied Victoria's mountain ash forests for two decades and knew people who were affected by the fires.

He says the most important lesson from the Black Saturday fires was the need to consider local, ecological and historical knowledge[52]:

- different forests produce different fires, meaning they require local knowledge, experience and management
- fire behaviour is heavily influenced by vegetation, such as the highly combustible mountain ash forests north and east of Melbourne, which require rare but catastrophic fires to regenerate
- local fire history is the best survival guide.

Communities' previous experience with fires can help them understand when the deadliest fire days are likely to occur, the distinctive patterns they follow and whether they may escalate. For example, during interviews with community members affected by the fires, Griffiths found that the elders in the township of Steels Creek knew where the fire would come from on a particular day and which parts of the Yarra Valley would burn. They also knew that the bunkers dug by sawmill workers early last century had saved many lives.

In the face of ever more extreme weather events, adopting historically proven practices, such as those informed by Australia's deep environmental and cultural inheritance, is increasingly important. Understanding Indigenous knowledges, including land management practices and cultural burning, provides long-term local fire histories of local areas[53].

Oral histories and testimonies form invaluable research collections to prepare for many different types of natural disasters. Research infrastructure that enables researchers and community members to document, archive and access this human experience allows us to learn from the past to help manage the future.

New Zealand has taken this approach in the wake of the 2010 Christchurch earthquake. A collaborative, open access archive for researchers and the community provides federated access to a broad range of material gathered by leading New Zealand cultural and educational institutions[54].

52 AAH-Power-Humanities-2015-All.pdf.

53 Land, resource & fire managers: Australia's First Peoples (humanities.org.au).

54 About | CEISMIC.

An image from the 'Ghost Trees' art installation by James McGrath and Gary Sinclair that uses drone and terrestrial laser scanning data and 'eco-acoustic' sound data collected at multiple Terrestrial Ecosystem Research Network environmental monitoring sites. The art explores the visual and emotional aspects of scientific data on the environment and has been exhibited in Australia and overseas. Image credits: James McGrath and Terrestrial Ecosystem Research Network.

Australia's research on digital society, culture, economics supports inclusive digital transformations across a range of industries including transport, public health, social services, education and national security. Such research draws on heterogeneous data sources and requires access to large-scale social data, longitudinal datasets and complex software models. New data sources, such as mobile and social data, allow researchers to model and understand the circulation of information, goods and services in ways not possible a decade ago.

Such collections, data sources and software models are the sectoral equivalent of the large-scale instrumentation-based facilities that are essential in other discipline areas. As most key datasets are not generated for research, they need domain-specific expert curation and access and licensing arrangements brokered with data holders.

Infrastructure that supports the HASS research sector plays a key role in ensuring the health, wealth and wellbeing of the nation.

For example, researchers across the HASS disciplines have been vital in responding to the COVID-19 pandemic. While scientists developed vaccines in record time, anthropologists, linguists, sociologists, ethicists and psychologists helped governments understand and navigate complex issues around vaccine engagement and distribution. This research community will continue to be crucial to Australia's COVID-19 recovery, making sense of the pandemic's social, economic and cultural consequences and advising government how best to proceed and mend.

A landscape analysis of research infrastructure in the UK found that HASS infrastructure includes "tools and techniques such as clusters of expert capability and provision of hardware or facilities. Many infrastructures collect or facilitate access to research objects, including physical resources such as historic artefacts and virtual resources such as social science data"[55]. A national approach to data for Australia must include new digital infrastructure capable of addressing and supporting the cultural and social aspects within national challenges, such as environment and climate change, food and beverage, space and technology.

Much of Australia's public sector data is underutilised. For example, research use of business, consumer and government administrative data is vital for understanding and addressing economic and productivity challenges. Further, critical high value data are collected and governed by multiple levels of government and must be integrated to derive key health, social and economic insights for policy makers. To be nationally significant and support cutting-edge research, innovation and translation to policy and practice, a national data platform must include Australian Government and state and territory datasets. Building on the work of the Office of the National Data Commissioner and the reforms that will flow from the introduction of the National Data Availability and Transparency Bill 2020[56], it is both important and timely to develop models that ensure relevant public sector datasets are more readily accessible to researchers.

Targeted infrastructure investment can continue to strengthen and support Australia's HASS sector and build on successful research frameworks with flow-on benefits to other parts of the research sector. The HASS Research Data Commons (HASS RDC, funded through NCRIS in the 2020 Investment Plan) is addressing challenges in data management, protection and utilisation in conjunction with existing NCRIS capabilities. Important HASS RDC developments under way include the Australian Text Analytics Platform, the Integrated Research Infrastructure for Social Science and the Language Data Commons of Australia.

However, the HASS RDC is nascent and critical capabilities still need to be developed, such as:

- the capacity for use of big data from digital platforms to address critical social and public interest issues
- interoperability of data and resource collections and tools to work across collection boundaries
- secure data labs to enable the interrogation of sensitive data sets support for other members of the galleries, libraries, archives and museums (GLAM) sector, including ongoing funding for collection digitisation to open more data
- the availability of (and capacity to collect, search, codify and analyse) a wide variety of non-textual sources/media
- tools and guidelines for data donation and citizen science approaches, including support for sophisticated crowdsourcing tools to annotate and enrich data
- machine learning tools to augment and accelerate management and analysis of diverse or complex data.

Roadmap consultations also identified further opportunities to improve the impact of HASS research by elevating existing capabilities to the national facility level to ensure greater networking and partnership. Opportunities include establishing an Australian Social Data Observatory (ASDO) and a national framework for collections, including digitisation.

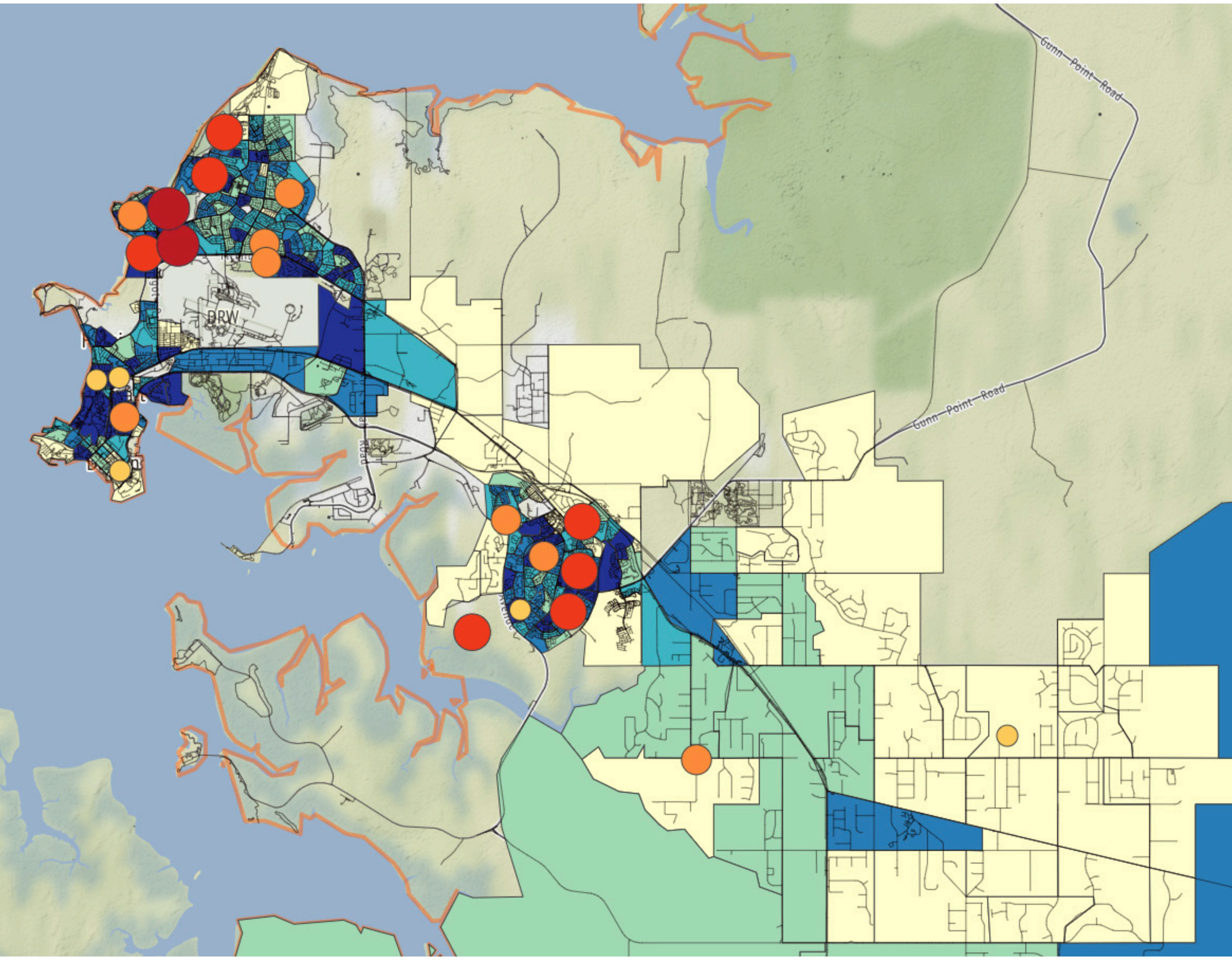
ASDO would provide tools and resources to deliberately gather and analyse online user experience data, dramatically extending access to social media data beyond the small group of specialists who currently work in the field. It would build on and consolidate existing activities involving multiple NCRIS projects, and other facilities and organisations (including the Atlas of Living Australia, Australian Research Data Commons, Australian Urban Research Infrastructure Network, National Computational Infrastructure, Population Health Research Network, Australia's Academic Research Network (AARNet), Trove – National Library of Australia). Such a capability would enable researchers across HASS and science, technology, engineering and mathematics (STEM), as well as government, industry and civil society to benefit from the insights derived from social data.

55 ***The UK's research and innovation infrastructure: Landscape Analysis***, UK Research and Innovation (UKRI).

56 National Data Commissioner, ***National Data Availability and Transparency legislation***, Australian Government, 2021.

Digitisation as a national capability would catalyse research access to relevant data sources including historic government records, heritage collections and clinical records. Responsibilities for a national digitisation capability could include:

- providing consistent advice and information about appropriate standards and guidelines for digitisation
- being a connector and facilitating collaborations and partnerships between researchers, digitisation suppliers and other partners such as GLAM organisations
- achieving effective procurement of data conversion services through better vendor relationship management and aggregating demand to achieve economies of scale
- preservation advice
- providing risk, copyright and licensing advice.



Spatial representation of socio-economic indices and access to homelessness services. Data via ABS and Infoexchange, created using AURIN Portal, Australian Urban Research Infrastructure Network.

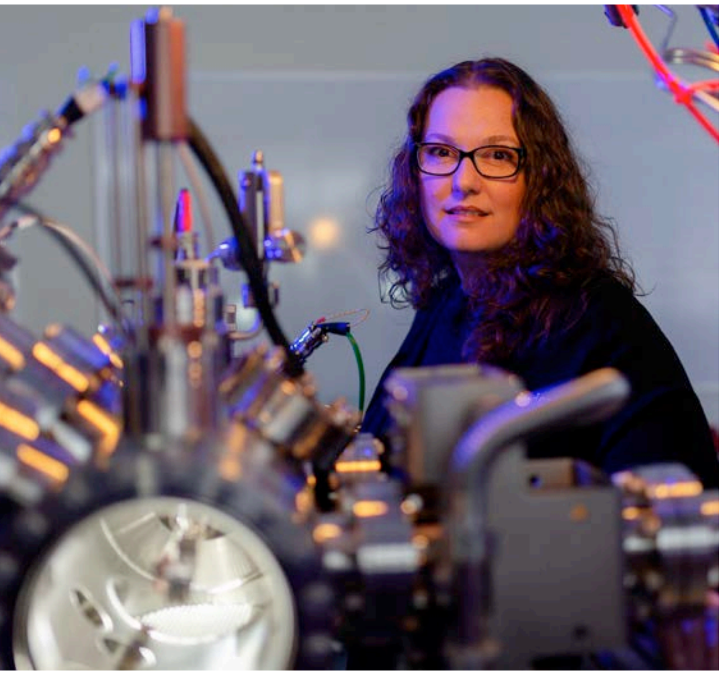
5.8 Industry engagement and research translation

Recommendation 6: Improve industry engagement with NRI

Although improving, there are barriers limiting effective engagement and research translation between NRI and industry. NRI needs to be more visible and accessible to industry and the mutual benefits from closer collaboration should be further promoted. Successful research translation will require a range of elements working together in harmony across jurisdictions. This includes the legal, governance, business and social licence frameworks needed to achieve real impact. The business models around NRI management need to adapt to enable greater research impact and reach.

Research outputs have the potential to deliver immense societal and economic benefits through translation into real-world interventions including technology, policy and practice. For this to happen, they must be accessible to the wide array of potential end users such as industry, governments, practitioners and the public. NRI provides the tools and environment for researchers and research end users to work together on practical solutions to shared problems, fostering innovation and research translation. Highly qualified staff provide expert advice to government, industry and researchers on practical and commercial applications of research.

Industry interactions with researchers can take on many forms, including the development of commercial products and services, and the creation of knowledge. These all share great potential for both economic and societal dividends. Australia's world-class NRI facilities and services can catalyse strong long-term industry and research partnerships, both domestically and internationally. With a focus on research excellence, NRI can also fill gaps at the early stages of research translation such as during prototyping and testing in the commercial application of research. This often falls outside the remit of university research and is too early to attract industry investment. In the same space, NRI facilities also provide advanced manufacturing capabilities to support industry ventures or provide testing and quality assurance frameworks.



Sarah Harmer of Flinders Microscopy with Australia's first photoemission electron microscope.
Image credit: Microscopy Australia

However, the Roadmap consultation process found that the industry sector has limited awareness of NRI, its benefits and how the facilities and resources can be accessed. There is low use of NRI by industry despite the clear benefits for industry and the research sector, and the Australian innovation system more broadly. This divide is potentially resulting in lost opportunity for commercial activities that could provide an alternate business model and funding mechanism for NRI facilities from industry. It also means that the true impact of the NRI is not being realised to its full extent beyond the research community.

Some of the barriers preventing industry from effectively engaging with NRI include:

- lack of awareness of NRI capabilities due to limited targeted industry promotion and networking
- difficulties accessing NRI, including time and resource constraints, and lack of technical capability and expertise to navigate the process
- issues with data management and quality frameworks.

CASE STUDY

Industry access made easy

The Australian National Fabrication Facility (ANFF) is working to lower the barriers to successful innovation and make access to micro and nanofabrication equipment easy for both academia and industry.

In addition to cutting-edge micro and nanofabrication equipment, ANFF provides a mixture of advanced training, expert assistance and process development support that isn't available anywhere else.

To overcome barriers to research translation, ANFF:

- operates the network as an IP neutral environment
- uses standard facility access agreements for new client companies
- operates as a not-for-profit to offer low-cost services
- plays matchmaker to help clients provide solutions to each other's R&D challenges.

One technology that has benefited from ANFF's support is the NanoMslide, a novel nanopatterned microscope slide that is being developed as a pivotal test in cancer staging and diagnosis. Invented by researchers at La Trobe University, the team behind NanoMslide are engaging with industry partners, with future plans to commercialise the technology through a new spin-out company, AlleSense.

However, AlleSense could not manufacture enough slides in Australia to meet demand. After scouring the world for a solution, ANFF-VIC and La Trobe University coinvested $500,000 to procure the Eulitha Phabler, a high resolution, high-throughput patterning tool. This will enable the company to produce thousands of units each month while it continues scale-up.

Importantly, the Phabler is now available to other Australian companies and will help advance research and development in the field of 2D metamaterials.

A microscope slide that can help detect cancer, developed using ANFF's NCRIS-funded nanopatterning equipment at the Melbourne Centre for Nanofabrication. Image credit: La Trobe University.

Although Australia produces excellent research, there is an opportunity to improve the delivery of commercial outcomes. The government continues to investigate opportunities to encourage and accelerate university commercialisation outcomes, including through consideration of proposed options for the University Research Commercialisation Scheme[57].

Although it is vital to maintain investment in research excellence and basic research, it is important to develop frameworks and cultural and environmental settings that support research translation and commercialisation. Improving connections between end users of research and NRI will increase the impact research can have on society.

Research is only one step in the process and requires many stakeholders to achieve real impact. A whole-of-ecosystem approach is required around common goals to concentrate efforts and includes true co-design and development across government, industry and research. The role of legal, governance and social licence frameworks is critical, and successful translation will require close engagement across areas such as engineering, design, business, marketing, logistics policy and regulation. Discovery happens in small teams, but innovation and impact requires the collective efforts and collaboration of a strong network.

The Roadmap consultation process identified key opportunities to increase industry sector awareness and use of NRI that will incentivise more cross-sector collaboration and partnerships. These opportunities are presented under five broad themes:

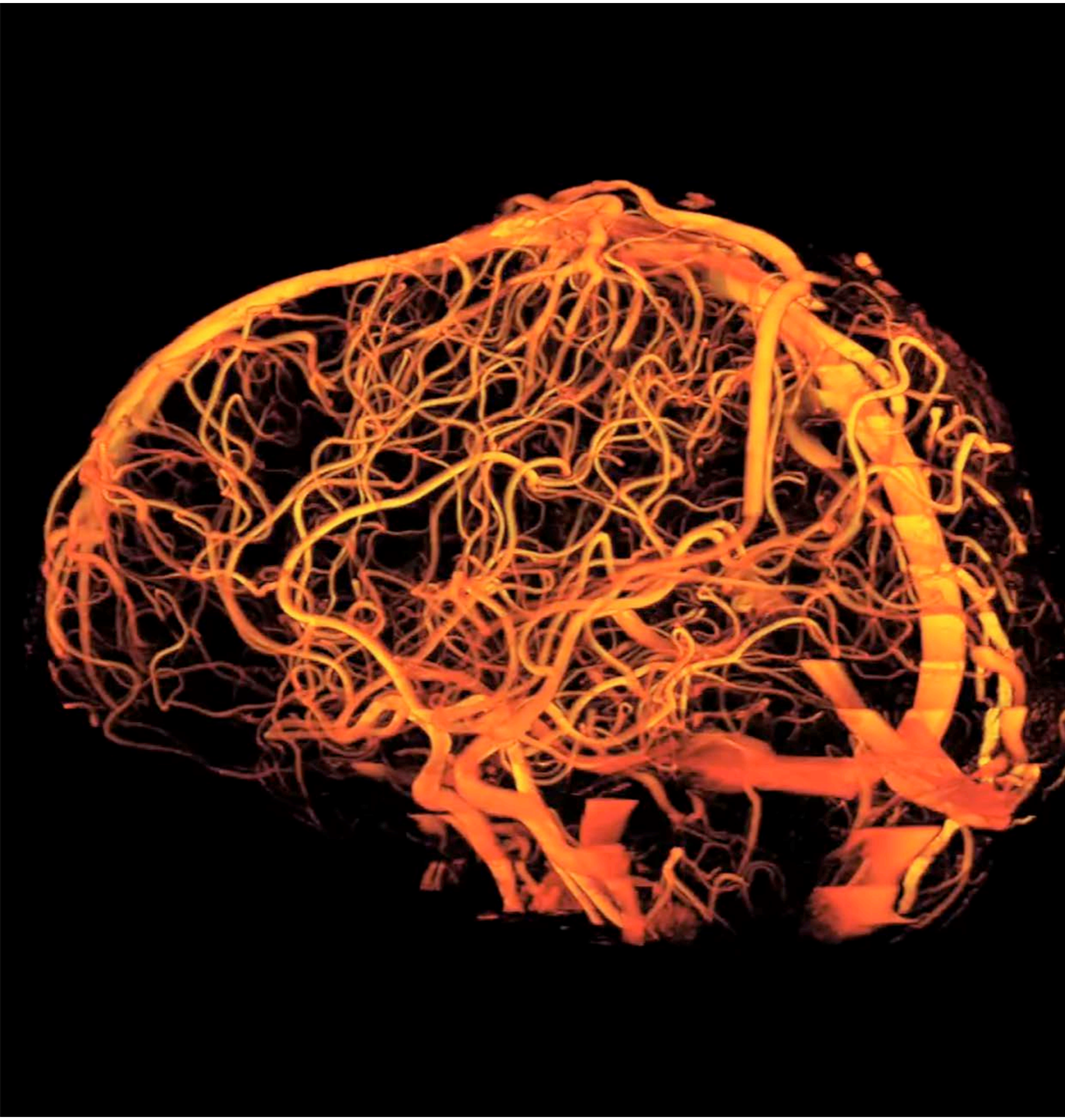
- *Adaptation, expansion or consolidation of existing NRI* – linked data networks, standardisation and centralisation of IP activities, expansion of testing and prototyping capabilities to support manufacturing.
- *People as crucial enablers* – NRI-embedded staff dedicated to industry engagement, mentors dedicated to supporting translation of research projects, research-industry exchange programs. Greater engagement with industry and translational research will also support the professional development and careers of NRI staff.
- *Raising the visibility and profile of NRI capabilities* – promotional activities like open days (both physical and virtual), representation at industry-based conferences, providing industry voucher programs to access NRI (and similar initiatives supported by state and territory governments) and publicly funded research agencies and establishing a broker/facilitator role.
- *Research-industry integration at the structural level* – grants for NRI-led research-industry partnerships, developing collaborative hubs co-located at NRI facilities, and a whole-of-NRI structure and governance review with industry sector input (such as the Quantum Commercialisation Hub[58]).
- *Improvements to data linkage, storage, management and access* – creating more standardisation and streamlining of data management frameworks to facilitate industry engagement.

Government should consider these opportunities to improve industry engagement as part of the 2022 Investment Plan. A starting point could be the establishment of a collaboration and information intermediary between industry and NRI. This could be done through Industry Collaboration Facilitator roles (with links to existing government initiatives such as Innovation Connections[59]) that connect across NRI projects, establish networks and raise awareness of collaboration opportunities with industry. New business models could be sought by NRI that meet the needs of industry and provide additional revenue streams to support NRI operations. Diversified funding streams for NRI projects could provide long-term benefits such as increased funding certainty facilitating long-term project planning. It could also provide incentives for projects to meet the needs of industry in addition to needs of research users. NRI efforts will benefit from coordination with other government-backed initiatives in commercialisation and industry growth and associated sector expertise, networks and delivery capabilities. It will be essential to consider the different research translation and industry growth strategies employed across the states and territories to ensure NRI is a connected and complementary participant.

57 Department of Education, Skills and Employment, ***University Research Commercialisation Consultation paper***, Australian Government, 2021.

58 Department of Industry, Science, Energy and Resources, ***New investment in Australia's quantum technology industry***, Australian Government, 2021.

59 ***Innovation Connections***, CSIRO.



Time-of-flight angiography of the human brain using 7T MRI at Queensland node of National Imaging Facility.
Image credit: National Imaging Facility

5.9 Development of a National Digital Research Infrastructure Strategy

Recommendation 7: Develop a National Digital Research Infrastructure Strategy

An important driver for maintaining quality research output is Australia's ability to generate and analyse data as well as improving the digital skills of researchers. Digital research infrastructure is fundamental to Australia's research effort and requires a National Digital Research Infrastructure Strategy. The Strategy will coordinate and integrate the national digital research infrastructure ecosystem and underpin collaboration at scale. This Strategy will support researchers across all fields by also providing the computing resources, digital tools, data governance frameworks and expertise needed to make best use of the data. It will streamline access to data and address computing, storage and analysis needs for researchers. The Strategy should be consistent with, and supportive of, other whole of government initiatives in this area, such as the *Digital Economy Strategy*[60] 2030 and *Australian Data Strategy*. The National Digital Research Infrastructure Strategy should be developed by government over the next year with any immediate insights feeding into the 2022 Research Infrastructure Investment Plan.

For the purpose of this Roadmap, NDRI is defined as: *DRI components that are collectively managed and operated as coordinated facilities and services for research institutions and users across the country because they are so nationally significant, or large in scale, complexity or cost that they cannot be offered by a single institution or facility.*

Previous NRI Roadmaps have highlighted DRI as essential infrastructure. It supports researchers across all fields of HASS and STEM, and over the entire breadth of the research spectrum from fundamental to applied research. Significant investment stemming from the 2018 and 2020 Investment Plans led to the formation of the Australian Research Data Commons, upgrading of HPC facilities and development of the software modelling infrastructure ACCESS-NRI. Since the 2016 NRI Roadmap, DRI has become even more integral to the Australian research sector for many reasons, including:

- the continuing exponential growth in data acquisition and its associated storage challenges
- research trends, such as the growth of AI/ML
- the increasing use of DRI and HPC in research areas such as genomics and bioinformatics
- the international push for open science which relies on integrated DRI and digitally skilled expertise.

To address the growing data and computing needs of Australian researchers, maintain research excellence and remain competitive on the international stage, a strategy to develop an integrated NDRI ecosystem is necessary. The NDRI Strategy should:

- coordinate and integrate existing national, institutional and commercial NDRI to streamline access for researchers and users
- provide direction on investments to address pressing issues including digital skills and expertise, data collections, data standards, data storage and data synthesis, analysis and visualisation
- plan and prepare for future challenges and opportunities including HPC, exascale computing, quantum computing, big data and commercial and non-commercial cloud services (e.g. Nectar Research Cloud, AARNet CloudStor).

60 Department of Prime Minister and Cabinet, ***Digital Economy Strategy 2030***, Australian Government.

The NDRI Strategy should address the following issues, as identified through Roadmap consultations:

Data access and interoperability

Access to high-quality data for research is a fundamental driver of innovation and excellence in all research disciplines. Researchers need to be able to access data from various sources including collaborators in their fields, researchers outside their research domain and international sources.

The use and reuse of data is a critical issue. NRI must make data accessible, and data generated through research within academia also needs to be accessible to government and other users.

Data is also increasingly generated, collected and stored outside of academia, such as in government agencies, the private sector and industry. The recently introduced National Data Availability and Transparency 2020 Bill will create significant reforms and there will be opportunities to explore the possible uses of business, consumer and government administrative data for research purposes.

There are regulatory and ethical factors that limit access to sensitive data (such as that pertaining to health), in addition to differences across state, territory and federal government policies. To address this, improved policies, procedures and mechanisms to allow for safe, secure and ethical access and use of data between researchers and across jurisdictions are needed.

Data also needs to be discoverable, interoperable and preserved for long-term use. Applying existing international data principles (such as FAIR) ensure that Australian research data is interoperable both domestically and internationally. Data generated, captured, stored and curated by NCRIS-funded projects is currently made available to the wider research community based on FAIR principles and appropriately implemented for individual research communities. FAIR, as well as the CARE (collective benefit, authority, responsibility and ethics) Principles for Indigenous Data Governance, need greater adoption across NRI and beyond academia.

Increased data accessibility and interoperability, supported by improved data governance through an NDRI Strategy, could ensure consistent data quality across the NRI ecosystem.

Data storage

Advances in computing, modelling and research tools and instruments have resulted in rapid growth of research data generation. To maintain this data as a national asset, data storage capacity needs to be improved for both working data and longer-term retention. So much data is being generated that on-site storage is needed, rather than storage at remote sites due to the cost of transferring data to computing resources or for analysis.

The cost of storage media is no longer falling quickly enough to offset increases in volume. Key issues that need to be addressed for longer-term and sustainable data storage solutions include:

- which data needs to be preserved
- where and how the data is stored
- who is responsible for the data
- who funds the necessary data repositories.

The NDRI Strategy could help address these issues by enabling the development of a national federated network of repositories and associated storage. It could also develop the terms by which such repositories could work with industry.

Trust and identity

An important aspect of providing researchers with access to high-quality data and storage resources is trusted access within the NRI ecosystem, as well as confidence in data quality. The Roadmap consultation process identified trust and identity as fundamental research infrastructure. Currently, this service is delivered by the Australian Access Federation but sits outside the NCRIS-funded NRI network. A system-wide approach to identity and access management would result in more secure research infrastructure and allow secure access and global connectivity for Australian researchers.

Furthermore, NRI investment would provide the capacity to develop cutting-edge trust and identity solutions to prepare for future cybersecurity risks and technology disruptors.

High performance computing

Both of Australia's Tier-1 HPC facilities (National Computational Infrastructure and the Pawsey Supercomputing Centre) have undergone major refreshes following the 2016 NRI Roadmap and 2018 Investment Plan. Due to the rate of technological advancement and significant capital costs, long-term strategic planning and investment is necessary to keep pace and effectively exploit new hardware.

While HPC is provided nationally by two Tier-1 facilities, access is limited due to strong demand and does not always suit researchers' needs. The NDRI Strategy should consider how NRI investment can increase the capacity and resourcing of existing Tier-1 facilities. Current HPC access schemes, prioritisation and resourcing need to be improved to account for increasing and more diverse researcher demands.

The first phase of Setonix (one of Australia's public research supercomputers) is located at the Tier 1 Pawsey Supercomputing Research Centre. It is named after the quokka, *Setonix brachyurus*. When fully commissioned, Setonix will be Australia's most powerful supercomputer with 30 times the combined performance of Pawsey's current systems. Image credit: Pawsey Supercomputing Centre

Some institutions have developed Tier-2 HPC to address these issues, but these facilities are not always widely available. Commercial cloud computing might offer suitable alternatives, but current offerings can be expensive and there may be issues regarding data protection and sovereignty.

To provide researchers with a more integrated ecosystem and further development of Tier-2 HPC, non-commercial cloud computing (e.g. Nectar Research Cloud, AARNet CloudStor) and commercial cloud computing is needed. Additionally, Graphics Processing Unit (GPU) infrastructure is seen as increasingly important for supporting AI applications. National access to GPU clusters is not currently equitable, inhibiting technology innovation that benefits SMEs.

Such an integrated ecosystem would likely be a mix or hybrid model that includes traditional and cloud, commercial and non-commercial providers and considers emerging opportunities such as hybrid quantum/HPC. It would also need to incorporate existing governance and access schemes.

Research software

Research software plays an essential but often invisible and undervalued role in generating, processing and analysing data. Software is an increasingly important element of DRI and its development needs to keep pace with hardware advances. Major advancements such as exascale computing will not be achievable without the equivalent development of exascale-ready research software.

Due to its importance, research software must be considered as research infrastructure itself. To ensure researchers can find and access the research software they need, it is important to also focus on the informatics services that underpin software assets. This would improve efficiency and reduce duplication of effort in developing new software solutions.

Software engineering is a highly specialised field; most researchers do not have the required expertise or capacity to develop software and do the necessary coding themselves as well as conducting their research. For this reason, the development and support of software infrastructure requires a dedicated workforce and a clear and sustainable business model.

Digital skills and expertise

The need for expertise and a skilled workforce is not limited to DRI and shares a lot of commonalities across the NRI ecosystem. This is discussed in *Chapter 5.2: Skills and workforce planning*.

Rapid advances in computing techniques and analysis, and management of large and complex datasets, have resulted in researchers no longer having sufficient expertise in data management, computational and analysis techniques.

Some research areas and institutions are already building data and computational expertise internally as an essential resource. The NDRI Strategy should consider how national, system-wide approaches to training and services could benefit researchers.

An integrated national digital research infrastructure ecosystem

Researchers do not need data, computing and storage independently of each other. Currently, some researchers navigate multiple schemes to access DRI. DRI investment should drive an integrated ecosystem which provides seamless access to data and computing in a timely way. This could include making allocations under one application or request.

Coordinated planning across the ecosystem is also necessary to address emerging challenges and opportunities such as exascale computing where the computing, data and software infrastructure must evolve and grow together to ensure no one component lags behind.

CASE STUDY

The value of a clear digital research infrastructure strategy

In 2012, the European e-Infrastructure Reflection Group proposed a single integrated digital ecosystem for the European Union (EU). At that time, resources were fragmented, difficult to access and there was little coordination.

The EU has since taken pan-European strategic approach. By pooling funds and coordinating institutions, they are developing and acquiring bigger, faster and more advanced DRI than any one country could alone. This also helps countries and regions that would otherwise lack access to world-class digital infrastructure.

An example of the EU's success is the European High Performance Computing (EuroHPC) Strategy. Before the strategy's implementation, one-third of global demand for HPC capabilities came from European industry, SMEs and researchers, but only 5 per cent of HPC capabilities were being provided by European HPC centres. Within 18 months of implementation the strategy resulted in computing power (in petaflops) multiplying by eight and increased available computing time beyond a factor of 10. With new access to digital resources, the strategy has supported the development of new translatable research and applications, contributing to creating a stronger, more connected HPC ecosystem.

The EuroHPC Strategy seeks to make the EU one of the world's top supercomputing powers and provide an integrated world-class HPC capability, high-speed connectivity and leading-edge data and software services. The Strategy demonstrates clear advantages to networking institutional Tier 2 HPC facilities with Tier 1 HPC and commercial cloud computing offerings. The Strategy also provides HPC training for more than 13,000 people, including domain-specific training and training on general HPC topics. This guarantees the significant investments in DRI across the EU are utilised to their full potential.

The scale of European DRI investment is unprecedented and broader than HPC alone. They are aiming to integrate HPC with other significant data and cloud infrastructure such as the European Open Science Cloud, quantum computing, AI, cybersecurity and digital twins. The breadth of the strategic approach to DRI allows data from non-academic areas such as government and industry to be put to use in a research context, generating new value and innovation opportunities. The end goal is to provide a coordinated, federated DRI system with a single point of access for all users to help them address big research challenges.

Image credit: Bigstock

6

Potential for step-change

As discussed throughout this Roadmap, Australia possesses a modern NRI system that is well-positioned to support researchers in addressing current and emerging challenges. The Roadmap consultation process has also highlighted the need to explore new opportunities while maintaining the momentum generated by existing NRI.

To drive Australia's research growth, step-change NRI investment needs to be considered. This investment:

- has significant application across the research and innovation sectors
- is large in scale and ambition
- further enhances Australia's sovereign capabilities
- supports Australia (where appropriate) to lead the world in research and/or the ability to collaborate.

Given the nature of national-scale research infrastructure, the Expert Working Group has sought to make recommendations to maximise the available investment, choosing to do a few things well.

The Expert Working Group has identified five areas which could focus NRI investment and deliver significant impact and step-change for Australian researchers and innovators. These areas will also contribute to the development of a modern Australian manufacturing sector by creating new industries, supporting existing ones and providing Australian innovators with a competitive advantage. The areas are:

- cutting-edge NDRI
- synthetic biology research infrastructure to deliver new bioindustries
- research translation infrastructure to drive increased industry investment
- world-leading environmental and climate infrastructure to underpin Australia's national adaptation strategy
- scoping future requirements to understand the opportunities that arise from taking a national approach to collections.

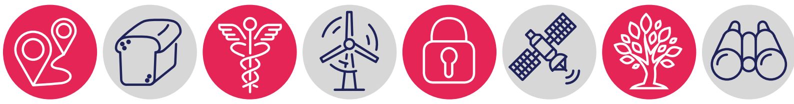
The above areas will require further investigation, as well as consideration of the current NRI network, investment partners and outcomes of the NRI pilots currently under development (in particular ACCESS-NRI, synthetic biology (biofoundry) and HASS Research Data Commons).

Recommendation 8: Prepare Australia to capitalise on future opportunities

The Expert Working Group recommends that Australia should enhance its sovereign capability with initial consideration given to the following NRI areas:

- cutting-edge national digital research infrastructure
- synthetic biology research infrastructure to deliver new bioindustries
- research translation infrastructure to drive increased industry investment
- world-leading environmental and climate infrastructure to underpin Australia's national adaptation strategy
- scoping future requirements to understand the opportunities of taking a national approach to collections.

6.1 Cutting-edge national digital research infrastructure



Cutting-edge computing and data services underpin every aspect of modern research. The future involves immense amounts of data from increasingly sophisticated and precise instrumentation. Its management will require key elements of computing processing power, data storage and expertise and researcher skills, alongside ecosystem-wide cooperation and planning.

Building Australian researchers' data, software and computing capability has the potential to deliver profound benefits and wide-reaching outcomes.

As discussed previously, a NDRI Strategy is necessary to coordinate and integrate Australia's diverse DRI landscape and streamline access for all users. However, for this strategy to be effective it must be accompanied by committed government investment and cooperation across the research ecosystem.

It is vital that NDRI is ready to address and capitalise on impending and future challenges and opportunities. These will represent major NRI investment and could include:

- the formulation of a clear Australian plan towards achieving exascale. Exascale computing could be a game-changer for Australian research and innovation.
- unified data storage solutions that allow data to remain close and accessible to computing services. This will require integration of existing disparate data repositories as well as building new repositories that are able to accommodate large-scale datasets.
- researcher training (data analysis and synthesis, AI/ML, data standards) to ensure that any data generated and stored will be FAIR, align with CARE principles and have appropriate metadata for use and reuse.
- a system-wide approach to identity and access management. This would result in more secure research infrastructure and allow secure access and global connectivity for Australian researchers. Investment would provide the capacity to develop cutting-edge trust and identity solutions to prepare for future cybersecurity risks and technology disruptors.

New levels of researcher skills, data capacity and step-change in HPC and cloud computing will transform Australia into a computing and data powerhouse. This environment will place Australian researchers and innovators at the forefront of international developments, and massively accelerate research and innovation outcomes and derived benefits across the full range of research challenges (*Chapter 3: Research themes, challenges and NRI impact*).

Automated sample preparation for genomic sequencing at the Garvan Institute of Medical Research, part of the Bioplatforms Australia network of facilities enabled by NCRIS. Image credit: Tim Levy

6.2 Synthetic biology research infrastructure to deliver new bioindustries

Biological research is undergoing a revolution, leading innovators to rethink their approach to biotechnology. Synthetic biology, which applies engineering principles to traditional biological disciplines, promises groundbreaking applications across agriculture and food production, precision medicine, the environment, biocontrol and sustainable low-emission industrial processes[61]. In short, synthetic biology has the potential to help address many of the challenges discussed in *Chapter 3: Research themes, challenges and NRI impact* through cutting-edge, transformative technologies that would underpin a strong Australian modern manufacturing sector. Existing strengths in biological and engineering research, a strong agricultural industry and access to Asian markets mean that Australia is well-poised to take advantage of this opportunity[62].

Synthetic biology research will benefit from the existing network of powerful NRI (omics, HPC and cloud computing), but has specific needs and will require dedicated infrastructure. This warrants purposeful investment in new, coordinated NRI that will bolster and dramatically expand the current nascent and piecemeal synthetic biology offering, which does not operate on the scale of a national service facility. To ensure value, synthetic biology infrastructure must also link into a strong Australian network of omics NRI. Synthetic biology NRI could include:

- biofoundries to streamline the engineering workflows that form the basis of synthetic biology research and discovery and allow the development of new bioproducts at an increased pace. As applications of synthetic biology expand, new types of biofoundries will become necessary to accommodate different biological systems and increased demands in capacity.
- researcher access to different types and scales of bioreactors that allow necessary scale-up and testing. Currently, there is limited opportunity for such testing but without these facilities, even the most groundbreaking laboratory discoveries cannot be translated into real-world applications. This investment would also align strongly with the broader need for translation NRI discussed in *Chapter 6.3: Research translation infrastructure to drive increased industry investment*.
- integrated and networked synthetic biology platforms to maximise synergies and efficiencies and avoid duplication. This requires interfacing with other Australian NRI and networking with international activities.
- skilled experts in the diverse techniques employed in synthetic biology to support physical and virtual facilities.

Together with a well-maintained existing biological NRI network, this investment will deliver world-class capacity in the development of new biological products and processes. This will place Australia at the forefront of this revolution and allow Australian industries to compete successfully on the international stage. The resulting research-innovation pipeline is also set to create new, disruptive bioindustries that will ensure future prosperity by underpinning a strong and sustainable bioeconomy that supports Australian net zero strategies and targets.

61 Australian Council of Learned Academies, ***Synthetic Biology in Australia: An outlook to 2030***, Office of the Chief Scientist, Australian Government, 2018.

62 Office of the Chief Scientist, ***Occasional Paper: Synthetic Biology in Australia***, Australian Government, 2020.

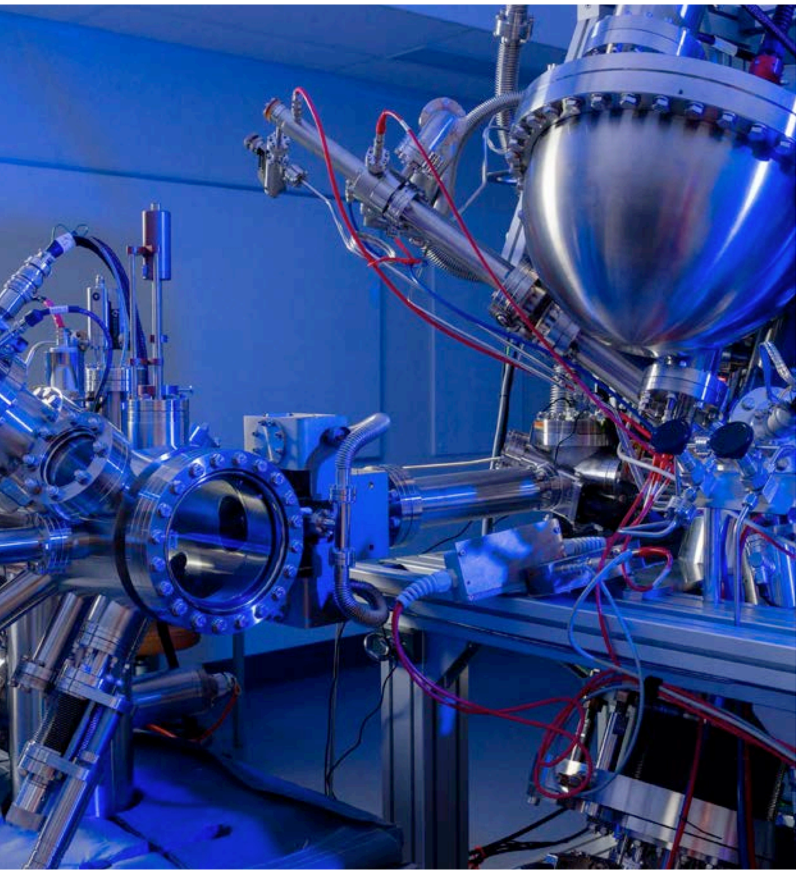
6.3 Research translation infrastructure to drive increased industry investment

The gap between research discovery and real-world impact is one of the most pervasive challenges faced by Australian research and innovation. Beyond ideation and discovery, much of the innovation value chain falls outside the traditional remit of university research but is still too early to attract industry interest and investment. Bridging this gap could deliver major impact and widespread social and economic benefits, through the translation of laboratory findings into tangible products, establishing first run production and prototyping and finalising research commercialisation in Australia.

Focused investment that builds a suite of translation NRI is necessary for researchers to validate their research outputs and demonstrate their commercial potential. In turn, this would attract commercial interest by de-risking investment and opening pathways to the final stages of product development that are supported by industry. Such NRI could include:

- applied engineering infrastructure that transforms cutting-edge research into working prototypes, suitable for testing and further development. This will support the translation of new and advanced technologies with high added value, such as smart sensors, IoT, precision measurement devices, advanced materials and space and aerospace technologies.
- openly accessible infrastructure that allows researchers and innovators to carry out scale-up testing of products and processes to demonstrate manufacturability of mature research outputs.
- open industry access to these NRI would boost industry engagement (Recommendation 6) and equip Australian enterprises with critical capabilities that currently fall outside their reach, greatly bolstering their ability to drive innovations and increase competitiveness.

Investment in these areas would contribute significantly towards eliminating the gap between discoveries and tangible products and better align the NRI system with demonstrating commercialisation outcomes. This will foster a business environment that encourages investment and supports job creation. It will also promote a focus on industry in the Australian science and technology system to boost productivity, scale and competitiveness. In this way, the wide-reaching potential of Australian research could provide real-world solutions that address the challenges discussed in *Chapter 3: Research themes, challenges and NRI impact*.



Flinders Microscopy's photoemission electron microscope.
Image credit: Microscopy Australia

6.4 World-leading environmental and climate infrastructure to underpin Australia's national adaptation strategy

In coming years, Australia will face unprecedented challenges due to changes to our climate and environment. World-class climate and environmental science is required to inform successful adaptation approaches that will help protect communities, infrastructure, industries, environments and biodiversity[63]. It will guide the process of adjusting to actual or expected changes in climate (reducing or avoiding negative impacts and exploiting beneficial opportunities) and galvanise the capacity of communities, environments and economies to cope with these changes. This is not feasible without a cutting-edge and integrated NRI system, geared towards collecting diverse climate and environmental data and predicting future changes. Australia's unique climate and environment impose particular demands that must be addressed by a suite of interconnected, world-leading NRI.

Although some Australian NRI is already directed towards these concerns (this is recognised as a theme in *Chapter 3: Research themes, challenges and NRI impact*), there is an urgent need for step-change in the pace and scale of activities, as well as unprecedented levels of integration and interconnectedness. NRI investment to enable this step-change could include:

- biodiversity collections that underpin biosecurity. It is estimated that 70 per cent of species that exist in Australia are unknown[64]. Standardising nomenclature and DNA sequencing these collections and type specimens in addition to their expansion and digitisation will create a crucial reference library for biodiversity and biosecurity and underpin ecosystem and climate modelling. This will enable the use of eDNA techniques to efficiently and effectively monitor freshwater, groundwater, marine and terrestrial ecosystems.
- better integration of environmental monitoring infrastructure, increased capacity in coastal and estuarial areas, freshwater and groundwater systems and enhanced and integrated atmospheric monitoring in urban and regional areas, including greenhouse gases and particulates. These investments will deliver comprehensive, world-leading environmental monitoring that will provide improved coastal management, management of pollutant sources and responses to bushfires and dust storms.
- foundational climate research and modelling to generate projections about Australia's future climate, and analysis of the probability of extreme events such as heatwaves, bushfires, droughts, floods and cyclones. A step-change in this capability will help identify regions and communities at greatest risk from climate threats and enable adaptation.
- environmental modelling that allows researchers to understand how ecosystems respond to change and future risks and uncertainties. Development and integration of this modelling system over the terrestrial, freshwater, groundwater, coastal and oceanic domains will create world-class infrastructure to support decision-making, adaptation planning and intervention strategies.

A world-leading integrated NRI system will support Australia's plan for net zero emissions by 2050[65] and the *National Climate Resilience and Adaptation Strategy*[66]. Accurate information is required to better predict, manage and adapt to climate change and will enable assessment of national climate impacts, evaluation of adaptation progress and continual improvement. The immense positive impact of meeting these objectives in future will extend across many of the major challenges identified in *Chapter 3: Research themes, challenges and NRI impact*.

63 Department of Agriculture, Water and the Environment, ***National Climate Resilience and Adaptation Strategy 2021–2025***, Australian Government, 2018.

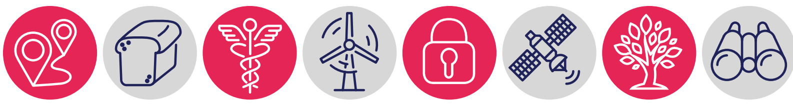
64 Deloitte Access Economics, ***Cost benefit analysis of a mission to discover and document Australia's species***, 2021.

65 Department of Industry, Science, Energy and Resources, ***Australia's long-term emissions reduction plan***, Australian Government, 2021.

66 Department of Agriculture, Water and the Environment, ***National Climate Resilience and Adaptation Strategy 2021–2025: Positioning Australia to better anticipate, manage and adapt to our changing climate***, Australian Government, 2021.

The Atlas of Living Australia is the Australian node of iNaturalist (inaturalist.ala.org.au), a global citizen science platform for recording and sharing species observations. Credit: rebelrebell55 (CC-BY-NC)

6.5 A national approach to collections



Australia has many unique and valuable collections that are critical for advancing research discovery, developing new industries, enriching education, connecting communities to nature and science, preserving biological and cultural heritage as well as managing biosecurity and other risks for Australia. These collections include biobanks, natural science collections, cultural collections, living collections, museums, botanical gardens, herbaria, research samples and longitudinal records.

Collections are used by researchers to investigate our natural world, society and history and increasingly offer powerful insights into threats such as climate change and natural disasters. These collections are currently uncoordinated at the national scale and their potential is unrealised.

Advances in new technologies such as AI/ML, digitisation, sample analysis, genomics and transcriptomics are transforming the way these collections can, and are, being used to unlock new research possibilities. Possibilities include bioprospecting for new sources of food, fibre and pharmaceuticals, early detection of invasive pests and pathogens, informing public health decisions, aiding the discovery of genetic disease causes and advancing personalised medicine.

A scoping study will help understand the potential opportunities that arise from taking a national approach to collections. This includes networking and leveraging existing investments and assessing the emerging capability needs and technology platforms.

7

Appendices

Appendix 1: NRI currently supported under the National Collaborative Research Infrastructure Strategy

NRI currently supported by NCRIS
Astronomy Australia Limited
Atlas of Living Australia
AuScope
Australian Centre for Disease Preparedness (CSIRO)
Australian Centre for Neutron Scattering (ANSTO)
Australian Community Climate and Earth Systems Simulator (ACCESS) – National Research Infrastructure (NRI)
Australian National Fabrication Facility
Australian Plant Phenomics Facility
Australian Research Data Commons
Australian Urban Research Infrastructure Network
Bioplatforms Australia
Centre for Accelerator Science (ANSTO)
European Molecular Biology Laboratory (associate membership)
Heavy Ion Accelerators
Integrated Marine Observing System
Marine National Facility: RV Investigator (CSIRO)
Microscopy Australia
National Computational Infrastructure
National Deuteration Facility (ANSTO)
National Imaging Facility
National Sea Simulator (AIMS)
Pawsey Supercomputing Centre
Phenomics Australia
Population Health Research Network
Southern Coastal Vessels
Terrestrial Ecosystem Research Network
Therapeutic Innovation Australia

Appendix 2: Terms of Reference

The 2021 National Research Infrastructure Roadmap (Roadmap) will set out Australia's research infrastructure capability and future areas of need for the next five to ten years. As the key policy document on Australia's national research infrastructure requirements it should enable Australia to maintain its research excellence, increase innovation and address emerging research challenges.

The Government committed to conducting a National Research Infrastructure Roadmap process every five years and Research Infrastructure Investment Plan every two years. The 2016 Roadmap provided advice to the Australian Government on future priorities for investment in key national research infrastructure capabilities. The Government responded to this with its 2018 and 2020 Investment Plans.

The 2021 Roadmap will be developed taking into consideration the current context, both in Australia and internationally. This will include examining lessons learned through the bushfire and COVID-19 pandemic crises and the degree of preparedness for similar issues in the future (in terms of infrastructure resilience). It will include the following analysis:

- Stocktake and review of Australia's national research infrastructure and investment since the 2016 Roadmap.
- Identify thematic areas for the 2021 Roadmap framework and the connection to Government priorities.
- Identify opportunities to maximise the impact and outcomes of existing research infrastructure investment.
- Identify opportunities to improve the level of collaboration through research infrastructure between the research and industry sectors and particularly small to medium size enterprises.
- Examine and identify emerging research infrastructure areas of greatest need for Government attention, including examining international trends.
- Examine where research infrastructure investment can support Australia to be world-class and provide international leadership.

An Expert Working Group with membership agreed to by the Minister for Education and Youth and the Minister for Industry, Science and Technology will lead the development of the 2021 Roadmap supported by a taskforce within the Department of Education, Skills and Employment with secondees from across Government agencies. This process will include the following activities and will culminate in a report to Government that outlines the Working Group's views on areas of future investment in national research infrastructure:

- seeking expert advice on research infrastructure capability and future research needs
- consulting with the research community, the university sector, research funders, state and territory governments, peak organisations, existing facility operators, publicly funded research agencies, private research institutes, international organisations, Government agencies and industry and business.
- providing stakeholders and the community with the opportunity to input on policy discussion papers and a draft Roadmap.
- providing updates on progress and presenting the final 2021 Roadmap to the Minister for Education and Youth and the Minister for Industry, Science and Technology.

The EWG is expected to deliver a report to government by the end of 2021.

Appendix 3: Expert Working Group

The Expert Working Group was comprised of members with expertise across government, research, business and investment:

- Dr Ziggy Switkowski AO (Chair) Chairman of NBN Co., Chancellor of the Royal Melbourne Institute of Technology
- Professor Barbara Howlett FAA (The University of Melbourne)
- Dr Michelle Perugini (Presagen)
- Dr Chris Roberts AO (Atmo Biosciences)
- Professor Liz Sonenberg (The University of Melbourne)
- Ms Lauren Stafford (Woodside Energy Limited)
- Mr Tony Cook (Department of Education, Skills and Employment)
- Dr Cathy Foley AO PSM (Australia's Chief Scientist)
- Ms Jane Urquhart (Department of Industry, Science, Energy and Resources)

Taskforce

The Expert Working Group was supported by the 2021 Roadmap Taskforce. The whole of government Taskforce is based in the Department of Education, Skills and Employment and includes experts from the Department of Industry, Science, Energy and Resources, Department of Agriculture, Water and the Environment and CSIRO. The members of the Taskforce were:

Ms Margaret Leggett, Ms Danielle Donegan, Ms Bernadette Kelly, Ms Mary Mulcahy, Dr Apostolos (Lee) Alissandratos, Ms Grace Campbell, Ms Michelle Chatelin, Dr Anu Choudary, Ms Mariana Dias Martins, Mr Jason Finley, Mr Nick Fishlock, Ms Cornelia (Nellie) Herbert, Dr Elaaf Mohamed, Ms Stephanie Priestley, Ms Claire Rider, Dr Edward Simpson, Ms Raffaela Santosuosso, Mr Tim Wotton and Dr Janine Young.

Appendix 4: Roadmap consultations

Due to travel restrictions, consultations for the 2021 NRI Roadmap were mostly conducted online. Over six months, the Expert Working Group and Taskforce members undertook extensive consultation using a variety of virtual platforms, including an online survey with nearly 3,000 respondents, a series of workshops, and two 'Ideas Jam' time-limited forums designed to promote the sharing of ideas.

Friday: The Creative Intelligence Collective coordinated consultations through a public website portal and email registration. Over 1000 people registered to receive email updates for consultation events and updates on the development of the Roadmap.

In February 2021, the directors of existing NCRIS projects expressed their vision for the next 5-10 years through a closed Ideas Jam. A second, open Ideas Jam in September 2021 focused on enabling better collaboration between industry stakeholders and NRI. Together, both Ideas Jams garnered 163 unique ideas with more than 600 comments.

In addition to broad-base consultation activities, targeted workshops and interviews were held on topics reserved for scoping studies in the 2018 Research Infrastructure Investment Plan. Workshops were held on national digital research infrastructure, biobanking, biosecurity and precision measurement to establish how to best incorporate these topics in the 2021 Roadmap. Products from scoping work on a NEPS NRI and precision measurement NRI were also hosted as discussion papers for comment online.

The Boston Consulting Group conducted a further three-week intensive stress test of the concepts and background information gathered by the Taskforce.

The Expert Working Group and Taskforce members consulted broadly with NRI stakeholders, including:

- Australia's Academic and Research Network
- Australian Access Federation
- Australian Council of Learned Academies and member academies
- Australian Government Interdepartmental Committee for the 2021 NRI Roadmap
- Australian Institute of Aboriginal and Torres Strait Islander Studies
- Australian Learned Academies
- Central Australia Aboriginal Health Science Network
- Cicada Innovations
- CSIRO
- Digital Research Alliance of Canada
- European Strategy Forum on Research Infrastructures
- Forum of Australian Chief Scientists
- Garvan Institute of Medical Research
- Government agency Chief Scientists
- Group of Eight
- Innovation, Science and Economic Development Canada
- International Centre for Radio Astronomy Research
- Key stakeholders of digital research infrastructure
- Key stakeholders of humanities, arts and social science research infrastructure
- Key stakeholders of marine research infrastructure
- Main Sequence Ventures
- National Collaborative Research Infrastructure Strategy Directors and Chairs
- National Network for Aboriginal and Torres Strait Islander Researchers
- New South Wales Chief Data Scientist
- State and territory governments and Chief Scientists
- United Kingdom Research and Innovation
- Universities Australia
- University Deputy Vice-Chancellors of Research

Appendix 5: Abbreviations and acronyms

Acronym	Description
2021 Roadmap	2021 National Research Infrastructure Roadmap
3D	Three-dimensional
AAL	Astronomy Australia Limited
ACCESS	Australian Community Climate and Earth System Simulator
ACDP	Australian Centre for Disease Preparedness
ACNS	Australian Centre for Neutron Scattering
AI	Artificial intelligence
AIATSIS	Australian Institute of Aboriginal and Torres Strait Islander Studies
AIMS	Australian Institute of Marine Science
ALA	Atlas of Living Australia
ANFF	Australian National Fabrication Facility
ANSTO	Australian Nuclear Science and Technology Organisation
APPF	Australian Plant Phenomics Facility
ARDC	Australian Research Data Commons
ASDC	Australian Scalable Drone Cloud
ASDO	Australian Social Data Observatory
AURIN	Australian Urban Research Infrastructure Network
BPA	BioPlatforms Australia
CARE	Collective benefit, authority, responsibility and ethics
CAS	Centre for Accelerator Science
COVID-19	Infectious disease caused by the SARS-CoV-2 virus
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DNA	Deoxyribonucleic acid
DRI	Digital research infrastructure
eDNA	Environmental DNA
EMBL	European Molecular Biology Laboratory
EO	Earth observation
EU	European Union
EuroHPC	European High Performance Computing Strategy
EWG	Expert Working Group

Acronym	Description
FAIR	Findable, accessible, interoperable and reusable
GCRF	Global Challenges Research Fund
GDP	Gross domestic product
GLAM	Galleries, libraries, archives and museums
GPU	Graphics Processing Unit
HASS	Humanities, arts and social sciences
HIA	Heavy Ion Accelerators
HPC	High performance computing
GDP	Gross domestic product
GLAM	Galleries, libraries, archives and museums
IDN	Indigenous Data Network
IMOS	Integrated Marine Observing System
IoT	Internet of Things
IP	Intellectual property
LIGO	Laser Interferometer Gravitational-Wave Observatory
ML	Machine learning
MicroAU	Microscopy Australia
MNF	Marine National Facility
mRNA	Messenger RNA
NCI	National Computational Infrastructure
NCRIS	National Collaborative Research Infrastructure Strategy
NDRI	National digital research infrastructure
NDF	National Deuteration Facility
NEPS	National Environmental Prediction System
NIF	National Imaging Facility
NRI	National research infrastructure
PA	Phenomics Australia
Pawsey	Pawsey Supercomputing Centre
PCR	Polymerase chain reaction
PHRN	Population Health Research Network
R&D	Research and development
RDC	Research data commons
RNA	Ribonucleic acid

Acronym	Description
SRI	Science, research and innovation
STEM	Science, technology, engineering and mathematics
STFC	Science and Technology Facilities Council
TERN	Terrestrial Ecosystem Research Network
TIA	Therapeutic Innovation Australia
UK	United Kingdom
UKRI	United Kingdom Research and Innovation
USA	United States of America