Australian Government

Department of Education, Skills and Employment

National Research Infrastructure Roadmap 2021

Exposure Draft

Stakeholders are encouraged to read the Exposure Draft and to provide feedback by responding to the targeted questions in the online form on the 2021 NRI Roadmap website. The consultation questions are:

The 2021 National Research Infrastructure (NRI) Roadmap aims to provide a roadmap and vision for NRI investment for the next 5 to 10 years.

1. *Are the recommendations appropriate to the current NRI environment?*
2. *Do the principles articulate the vision and key elements required of NRI, including investment?*
3. *The NRI Roadmap has a clear focus on identifying the NRI investments required to support Australian research over the next 5 to 10 years. Are there any national research infrastructure needs missing in the draft Roadmap?*
4. *A key priority for Australia is to enhance research translation. The 2021 NRI Roadmap identifies some reforms and investments to achieve this. What other reforms would help deliver this priority?*
5. *The Roadmap proposes that Australia could make landmark investments to drive step changes in research and innovation over the next 10 to 15 years. Do you agree with the assessment of potential areas for investment in the report? What other areas do you consider might fit the definition of landmark investment?*
6. *Please add any other comments you would like to provide to the Expert Working Group.*

All responses are limited to 300 words per question. You can upload additional information on the website however submissions over 1,000 words may not be considered.

Feedback closes 5pm (AEDT) Wednesday, 22 December 2021.

Feedback will be shared with the Expert Working Group and will guide the delivery of the final 2021 National Research Infrastructure Roadmap which will be delivered in early 2022.

Contents

Executive summary

Road to stability and maturity

National research infrastructure (NRI) comprises a range of nationally significant assets, facilities and services that support leading-edge research and innovation. However, it is much 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. Investigating the national research infrastructure our researchers need to support these endeavours has never been more important.

The 2021 National Research Infrastructure Roadmap (Roadmap) details a clear path for Australia to maintain existing NRI strengths while also delivering a step-change in capability. These proposed NRI investments will ensure Australian research remains competitive internationally, protects uniquely national assets, manages sovereign risk and helps create new industries.

The Expert Working Group believes that the following must be considered when planning for the future research 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 our research effort. In times of uncertainty, NRI is especially important. The current investment in NRI enabled Australia to respond quickly to the challenges of the 2019–2020 bushfires and the COVID-19 pandemic.

- there is an opportunity for Australia to make key investments in NRI, delivering a step-change in research that can improve our standard of living, strengthen our economic standing and build sovereign capabilities to protect Australia's interests.

- NRI needs to engage more effectively with industry and other research end users. This will help to future proof the NRI investment and lead to greater translation of research.

Finding 1:

The current NRI network 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 capacity provides an essential base to support government priorities such as the Modern Manufacturing Strategy, the National 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 facilities and their ability to support a broad range of research needs 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 but there is a need to review the principles to ensure they continue to meet the evolving needs of modern research.

Finding 3:

Australia's investment in NRI involves a collaborative approach to supporting the research sector. Co-investment brings a diversity of perspectives, increases creativity and capacity across the system and helps deliver return on investment. Infrastructure investment is about creating an ecosystem of expertise, infrastructure and services to support researchers. The human capital required to operate the NRI is equally important in achieving research outcomes.

Finding 4:

Exponential growth in data across all disciplines will be a critical challenge for the NRI over coming years, highlighting the need for integration of computing and data infrastructures 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. The research with the greatest impact is derived from collaboration across the science, technology, engineering and maths and humanities, arts and social sciences disciplines[1]. The creative arts, humanities and social sciences 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 technology. 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. These developments could be further emphasised 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 will place Australia at the cutting edge of research over the next decade and develop greater levels of sovereign capability.

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[1] Australian Academy of Science, *Advancing data-intensive research in Australia*, Australian Academy of Science, 2021.

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 protect Australia's interests and build capacity where there is a need to maintain 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 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.

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 (Commonwealth and State and Territory Governments, industry and the research sector) and where the most impact can be delivered.

Recommendation 5: Drive a more integrated NRI ecosystem

Modern research occurs across disciplinary boundaries to address increasingly complex problems. This requires linkages, interaction, 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 across the NRI system. 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 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 change 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 strategy. The strategy will coordinate and integrate the national digital research infrastructure (NDRI) ecosystem to streamline access to data, computing and analysis needs for the research sector. This strategy will support researchers across all fields by not only maximising the data available, but also providing the computing resources and digital tools and expertise needed to make best use of the data. 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 NDRI strategy should be developed by Government over the next year with any immediate insights feeding into the 2022 Investment Plan.

Recommendation 8: Prepare Australia to tackle future challenges

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.

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 the 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, National Climate Resilience and Adaptation Strategy, National Science and Research Priorities, the Blueprint for Critical Technologies, Australia's Long-Term Emissions Reduction Plan and the University Research Commercialisation Scheme. 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.

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* focusses on large step-change investments to create new Australian sovereign capabilities.
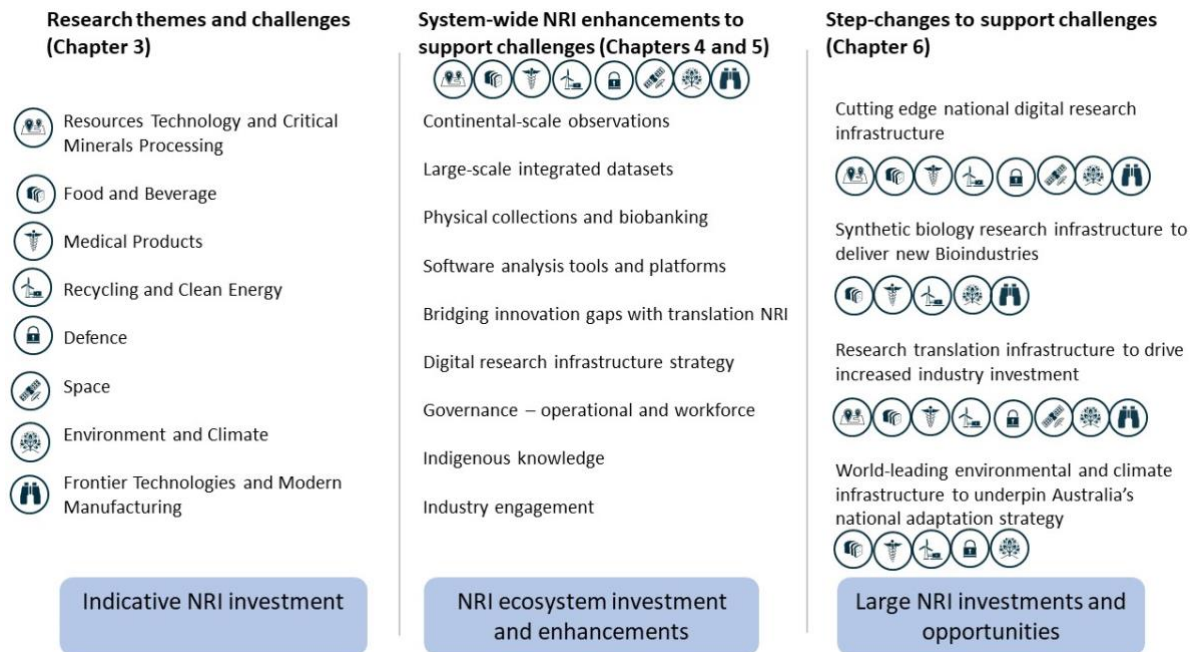
Research themes and challenges (Chapter 3)

- 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
- Digital research infrastructure strategy
- Governance – operational and workforce
- Indigenous knowledge
- Industry engagement

NRI ecosystem investment and enhancements

Step-changes to support challenges (Chapter 6)

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

Large NRI investments and opportunities

Figure 1: Overview of 2021 NRI Roadmap Exposure Draft

The Roadmap is only one element of a complex system of interconnected components that supports and enables Australia's research and innovation system. The 2021 Roadmap has been informed by the many policies, decadal plans and roadmaps delivered across governments. The development of the 2021 NRI Roadmap has considered the changing nature of research both in Australia and internationally, National Collaborative Research Infrastructure Strategy (NCRIS) investment since the 2016 Roadmap, current NRI and opportunities and lessons learned from the current COVID-19 crisis and 2019–20 bushfires.

The vision presented through the 2021 Roadmap will inform government funding decisions under future Research Infrastructure Investment Plans (Investment Plans).

1.2 NRI definition

The 2021 Roadmap applies the same definition of NRI as that used in the 2016 Roadmap[2].

NRI comprises the nationally significant assets, facilities, and services 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

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

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[2] Australian Government, *2016 National Research Infrastructure Roadmap*, Australia, 2016.

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 healthcare 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 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 level of funding provided, including NCRIS and other SRI programs over the period 2019–21.

Figure 2: SRI Budget Tables by program ($m) – 2019–21[3]

Australia's research infrastructure system is comprised of four layers that work together as an ecosystem (Figure 3)[4].

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 Square Kilometre Array and Australian Synchrotron is provided

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

[4] Australian Government, *2016 National Research Infrastructure Roadmap*, Australia, 2016.

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 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. Consideration of potential landmark NRI investments is discussed in *Chapter 6: Potential for step-change*.
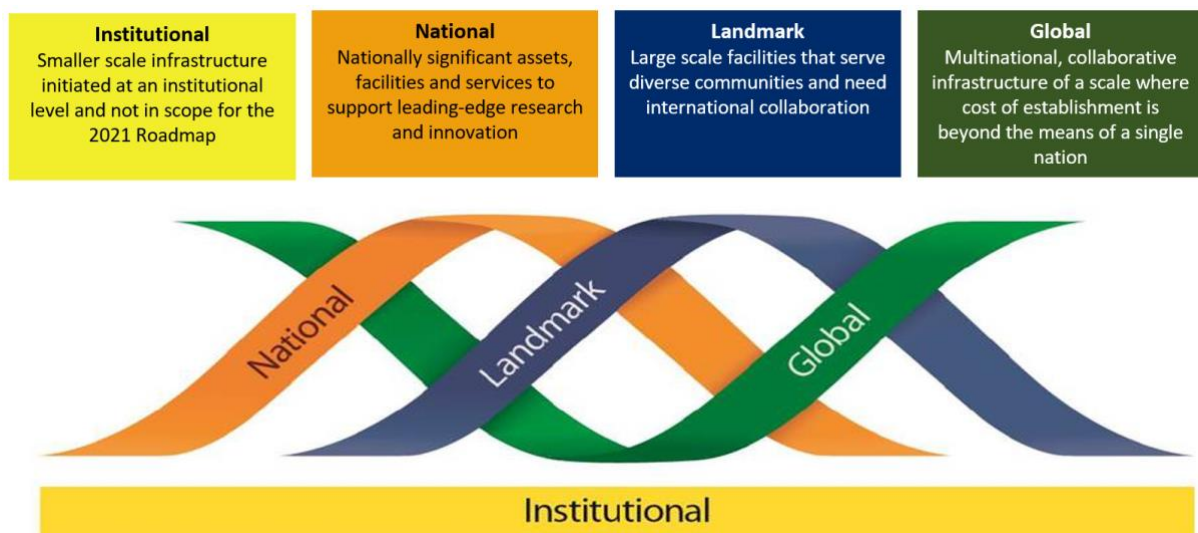

| **Institutional** | **National** | **Landmark** | **Global** |
| Smaller scale infrastructure initiated at an institutional level and not in scope for the 2021 Roadmap | Nationally significant assets, facilities and services to support leading-edge research and innovation | Large scale facilities that serve diverse communities and need international collaboration | Multinational, collaborative infrastructure of a scale where cost of establishment is beyond the means of a single nation |

Figure 3. Australian research infrastructure 'layers'

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

- 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 maintain 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 provides 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 to government priorities.
>
> - NRI includes the people, skills and knowledge, data, processes and equipment required to realise the value of the NRI.
>
> - NRI resources are focussed 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 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 facilitate and enhance 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

2.1 Emerging research 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.

NRI already 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.

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.

- 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 carefully interpret results.

- Increased collaboration, within and between different research areas and with industry, will require facilities to be multipurpose and serve many disciplines and industries.
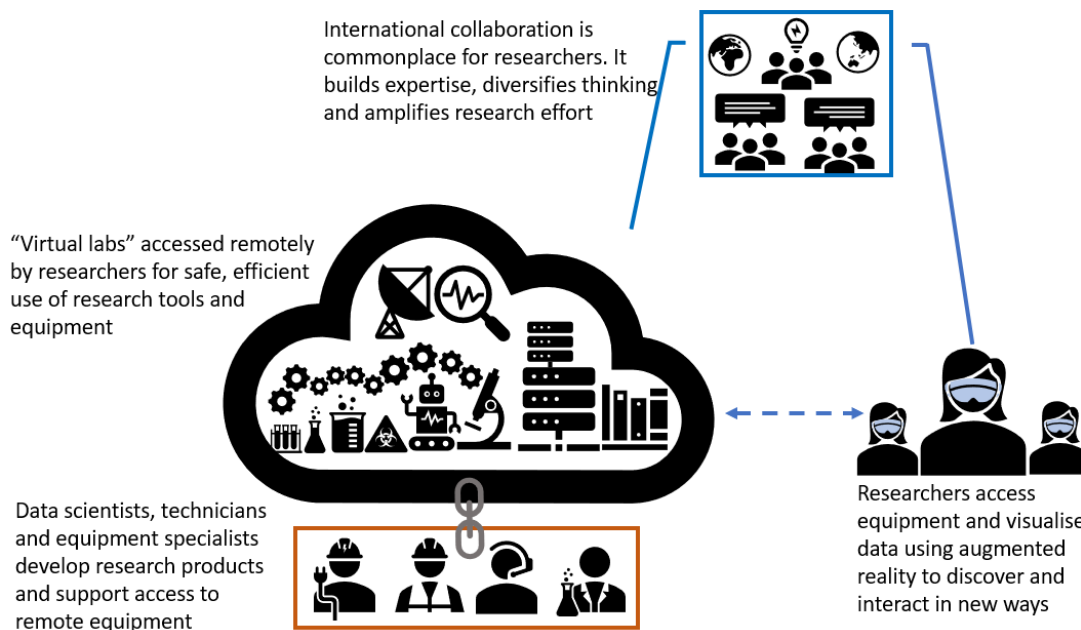
International collaboration is commonplace for researchers. It builds expertise, diversifies thinking and amplifies research effort

"Virtual labs" accessed remotely by researchers for safe, efficient use of research tools and equipment

Researchers access equipment and visualise data using augmented reality to discover and interact in new ways

Data scientists, technicians and equipment specialists develop research products and support access to remote equipment

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 knowledge:* there is increasing awareness and recognition of the potential for Indigenous knowledge to help solve some of our biggest research challenges. Indigenous cultures and practices can guide development and sustainable use of Australian lands and waters[5]

- *Next generation Omics*: integrated genomics, phenomics, 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 monitoring and bioprospecting, precision medicine and agriculture.

- *Quantum technology*: quantum science and technology, such as quantum sensing and computing, is increasing in importance. Advances in these areas will drive revolutionary changes across a range of technologies such as quantum sensors to enable discovery of valuable ore deposits and efficient groundwater monitoring, and quantum computers that support accelerated drug development through quantum chemistry simulation[6].

- *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

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[5] 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.
[6] CSIRO, *Growing Australia's Quantum Technology Industry: Positioning Australia for a four billion-dollar opportunity*, Australian Government, 2020.

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 and high-temperature 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.

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[7].

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, similar to 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, Innovation, Science & Economic Development 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

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

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 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. Such initiatives will likely increase the federation of research infrastructure in the digital domain.

Internationally, novel humanities, arts and social science (HASS) research infrastructures have been created that provide 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 infrastructures, bringing 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 infrastructures create 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 is often allocated on short-term funding cycles (particularly for operations). Various national approaches are used to encourage research infrastructures 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.

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[8], 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

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[8] UK Research and Innovation, *UK Research and Development Roadmap*, 2021.

- 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.

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 the Appendix.

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 collaboration 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)[9].

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*.

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 multi-laterally or bi-laterally. These partnerships occur at various levels, ranging from institutional through 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 primary drivers for Australia to participate in global research infrastructure projects are:

- leadership and direction setting, particularly in new or emerging areas
- 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 beyond Australia's financial capability, such as optical astronomy and advanced physics.

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

NCRIS facilities are engaged in formal and informal collaborative arrangements with organisations around the world. International engagement includes Memoranda 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 Government's 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 ACCESS climate simulator
- 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 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 in Chapters 3 to 6.

3. Research themes, challenges and NRI impact

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* – *W*e 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* – *S*pace 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* – *D*eveloping and translating critical technologies required to support modern manufacturing and secure supply chains. Success will include investment in research and commercialisation of critical technologies.

Eight themes have 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[10], the National Climate Resilience and Adaptation Strategy, the National Science and Research Priorities[11], the Blueprint for Critical Technologies[12], Australia's Long-Term Emissions Reduction Plan[13] and the University Research Commercialisation Scheme[14]. This challenge-focussed approach to identifying NRI and its impacts is consistent with the approaches of international roadmaps.

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 infrastructures identified in Figure 5 are indicative and serve to start discussion of current and future NRI needs through the Roadmap. Some of these infrastructures feature 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 infrastructures, metrology and precision measurement, microscopy, and particle accelerator 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*).

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[10] Department of Industry, Science, Energy and Resources, Modern Manufacturing Strategy, Australian Government, 2020.

[11] Department of Industry, Science, Energy and Resources, Science and Research Priorities, Australian Government, 2015.

[12] Department of the Prime Minister and Cabinet, Blueprint for Critical Technologies, Australian Government, 2021.

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

[14] Department of Education, Skills and Employment, University Research Commercialisation Scheme, Australian Government, 2021.

Figure 5: 2021 NRI Roadmap themes and challenges

2021 NRI ROADMAP THEMES AND CHALLENGES

	1. Resources Technology and Critical Minerals Processing	2. Food and Beverage	3. Medical Products	4. Recycling and Clean Energy	5. Defence	6. Space	7. Environment and Climate	8. Frontier Technologies and Modern Manufacturing
Theme / 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.	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	• 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 research	• National integration of large-scale health datasets • Biologics development facilities • Small molecule designing, synthesis testing and drug development facilities • National facilities supporting pre-clinical and clinical research	• Advanced renewable and other zero emissions technology • Hydrogen energy development and storage testing facilities • Publicly accessible national energy database	• Cybersecurity data ecosystem coordination, encryption technology • Nuclear materials development and analysis infrastructure • Defence materials, components and equipment development	• Optical and radio astronomy infrastructure and data storage • Astronomy precision measurement infrastructure • Earth observation infrastructure • Space exploration	• Biodiversity monitoring, collection and analysis infrastructure • Networked environmental modelling infrastructure • Integrated, publicly accessible environmental datasets • Marine, coastal and atmospheric monitoring and observation equipment • Climate and adaptation modelling	• Robotics infrastructure • Nanofabrication infrastructure • Space-related manufacturing • Quantum technologies • Synthetic biology infrastructure • Omics facilities • Imaging infrastructure • Support for user experience and human centered design

Links to national priorities

National priorities

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

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 National Science and Research Priorities (Resources), the Modern Manufacturing Strategy (Resources Technology & Critical Minerals Processing) minerals, 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
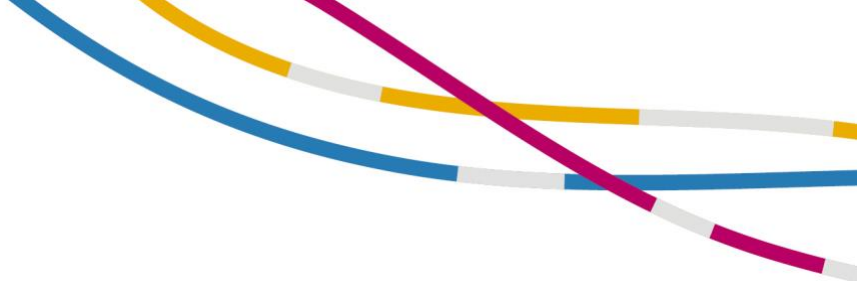
- improve environmental impact.

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 (ESG). Australia is a founding partner of the Energy Resources Governance Initiative (ERGI)[17] along with Canada, Peru and the United States, and is working with like-minded countries through the International Standards Organisation to ensure international standards support ethical, sustainable and secure supply chains.

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[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

    o 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

    o 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.

- Multi-purpose mineral and material processing facility

    o A mineral and material processing facility provides support for efficient extraction of minerals and the transformation of raw inputs into value added chemicals and materials. Also, the development of technologies that will allow lower-grade ores to be mined can be supported. This facility would also 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.

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

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

the agricultural sector. Innovation that transforms the properties (e.g. nutritional value and shelf life) of local produce, 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 National Science and Research Priorities (Food and Soil and Water), the Modern Manufacturing Strategy (Food & Beverage), the Blueprint for Critical Technology (opportunity to help us solve agricultural and environmental issues), the National Agricultural Innovation Agenda[19], the National Climate Resilience and Adaptation Strategy[20], 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 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, '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 due to reduced runoff 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[21]. 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, as well as a strong and robust biosecurity systems to manage the risks of pests and diseases.

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

[20] Department of Agriculture, Water and the Environment, National Climate Resilience and Adaptation Strategy 2021-2025, Australian Government, 2021.

[21] ACOLA, Future of Agricultural Technologies, Australian Government, 2020.

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 includes to collect, analyse, integrate and share data on parameters such as soil moisture content, nitrogen content, crop canopy height and plant and animal health will enable modelling of crop and livestock performance. This will enable increased productivity in the face of constrained resources and environmental change, efficient pest tracking and managing biosecurity risks.

- Biocontainment facilities for pathogen research
    - Biocontainment facilities for pathogen research includes both PC4 and networked PC3 laboratories. Facilities to deal with plant pathogens and pests would complement Australia's current animal biocontainment facilities. Ensuring geographical accessibility to limit potential pathogen exposure during sample transport is needed for both plant and animal pathogens. These facilities would protect Australia from both plant and animal biosecurity threats.

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 and technologies has the potential to improve quality of life and decrease health related costs. This includes smart monitoring devices and diagnostics, personalised implants, high-value therapeutics, cutting-edge treatments (e.g. regenerative medicine and genomics), and digital integrated products and platforms.

Addressing this challenge aligns with government priority frameworks including: the National Science and Research Priorities (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[22].

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[22] Department of Health, The Australian Medical Research and Innovation Priorities 2020–2022, Australian Government 2020.

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 lead to new and innovative treatment and disease prevention options. Precision medicine can change how healthcare is delivered by ensuring personalised treatments. 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 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 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.

- National facilities supporting pre-clinical research and clinical research.
  - Pre-clinical 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 has been identified through Roadmap consultation.

- o Clinical research support involves support for clinical trials including the scale-up of drug production.

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 up export opportunities by capturing greater value from our IP. Remanufacturing can also address our waste problem and offers 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 the 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 National Science and Research Priorities (Energy), Modern Manufacturing Strategy (Recycling & Clean Energy), the Blueprint for Critical Technologies (opportunities to address agricultural and environmental issues) and Australia's Long-Term Emissions Reduction Plan (Emissions Reduction), the National Hydrogen Strategy[23], the Technology Investment Roadmap[24], the Future Fuels and Vehicles Strategy[25], annual Low Emissions Technology Statements[26], 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[27]

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

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

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

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

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

- low emissions technologies could provide new export revenue for Australia of over $30 billion annually[28]

- a circular economy has the potential to generate 17,000 jobs and add $210 billion to GDP by 2047–48.[29]

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, supported by appropriate dedicated expertise.

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

  o Renewable and zero emissions technology development facilities, include prototyping and pilot testing equipment to aid in the scale-up of zero emission technologies.

- Hydrogen development and storage testing facilities

  o 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

  o A publicly accessible national energy database comprises open-access, integrated deidentified datasets on consumer energy consumption from the Australian Energy Market Operator and Distributed Network Service Providers.

- Support for user experience and human centred design research.

  o Human centred design ensures technology is designed with the human perspective from the outset, and in all steps of its development. Social licence research is integral to the uptake and trust of new technologies and will require access to datasets and expertise.

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[28] Department of Industry, Science, Energy and Resources, *Technology Investment Roadmap: Low Emissions Technology Statement 2021*, Australian Government, 2021.
[29] KPMG Economics, *Potential economic pay-off of a circular economy*, April 2020.

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 Modern Manufacturing Strategy (Defence), the Blueprint for Critical Technologies (risk of increased cyber-security threats), the Defence Science and Technology Strategy 2030[30], National Security, Science and Technology Priorities[31], the Defence White Paper[32], and the Defence Industrial Capability Plan[33].

Addressing this challenge has the additional benefits of:

- further bolstering Australia's defence industry potential for job creation and driver of 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

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[30] Department of Defence, *Defence Science and Technology Strategy 2030*, Australian Government, 2020.

[31] Department of Defence, *National Security Science and Technology Priorities*, Australian Government, 2020.

[32] Department of Defence, *2016 Defence White Paper*, Australian Government, 2016.

[33] Department of Defence, *Defence Industrial Capability Plan*, Australian Government, 2020.

- o   Cyber security 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.

- Nuclear materials development and analysis infrastructure

- o   This includes support for the monitoring and characterisation of waste products and related infrastructure development in both radioactive and non-radioactive environments. There is also expected to be increased expectations for research infrastructure to deliver nuclear training.

- Defence materials, components and equipment development

- o   Sovereignty and defence manufacturing base and defence R&D, including development and integration of emerging technologies, testing and prototyping, scale up manufacturing of products and components supporting Australian defence priorities.

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.

Space capabilities underpin innovation in communications, navigation (GPS), space situational awareness, and Earth observation capabilities.

Addressing this challenge aligns with government priorities including the Modern Manufacturing Strategy (Space) 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[34]

- 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[35]

- augmenting the Civil Space Strategy's ambition of stimulating more than $1 billion of capital investment in Australia's civil space industry by 2028[36].

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

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[34] Australian Space Agency, *Advancing Space: Australian Civil Space Strategy 2019-2028*, Australian Government, 2020.

[35] *CSIRO Earth Observation Data*, Australian Government 2021

[36] Australian Space Agency, *Advancing Space: Australian Civil Space Strategy 2019-2028*, Australian Government, 2020

advance 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.

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

- Earth observation infrastructure

  o Earth observation infrastructure includes satellite imaging, sensor networks, lidar technologies, data storage and ground calibration sites.

- Optical and radio astronomy infrastructure and data storage

  o Optical and radio astronomy infrastructure includes both domestic infrastructures and participation in international projects such as the Square Kilometre Array. It also includes large-scale data storage.

- Astronomy precision measurement infrastructure

  o Astronomy precision measurement infrastructure includes the Laser Interferometer Gravitation-Wave Observatory (LIGO) and related high-sensitivity instruments, for enhanced detection of gravitational waves and measurement of the optical field. This involves participation in international collaborations such as LIGO.

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. Australia's unique ecosystem and environment must be protected so that it can adapt to climate change. 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.[37]

Addressing this challenge aligns with government priority frameworks including: the National Science and Research Priorities (Environmental Change) and the National Climate Resilience and Adaptation Strategy.

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

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.[38]

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 focusses on environmental observation improves the understanding of Australia's terrestrial, atmospheric, coastal and ocean environments.

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.

- Marine, coastal, freshwater and atmospheric monitoring and observation infrastructure
    - Marine, coastal, freshwater and atmospheric monitoring and observation infrastructure includes sea-floor mapping vehicles, observation and monitoring of Australia's coastal, estuarine and freshwater environments and atmospheric measurement.

- Integrated, publicly accessible environmental datasets
    - Integrated publicly accessible environmental datasets include urban, biodiversity, terrestrial, ocean, freshwater, estuarine and atmospheric datasets from state and territory monitoring programs and NRI. Additionally, it includes large-scale collections of earth, soil and water samples.

- Networked environmental modelling communities
    - Networked environmental modelling communities enable the sharing of data and models across research communities such as that proposed by the National Environmental Prediction System (NEPS) scoping study. NEPS includes a synthesis capability, modelling infrastructure and governance hub.

- 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

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

monitoring flux stations for increased ecosystem data collection) and open-source climate adaption datasets.

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 National Science and Research Priorities (Advanced Manufacturing) 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 infrastructures:

- Robotics infrastructures

    o 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

    o Nanofabrication infrastructure includes metrology infrastructure for lithography, etching and deposition. 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

    o Space-related manufacturing infrastructure supports upgrading existing products to develop complex and integrated aerospace solutions, and to increase global value chain operations in aerospace.

- Quantum technologies infrastructure

    o 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

    o 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

    o 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.

- Advanced imaging facilities

    o Advanced imaging facilities include transmission and scanning electron microscopes and X ray photoelectron spectroscopes to characterise biological and non-biological materials. Additionally, imaging facilities (such as magnetic resonance imaging, positron emission tomography and computed tomography scanners) are used in preclinical studies.

- Support for user experience and human centred design research.

  o 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.

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 the challenge of Space:

- the National Computational Infrastructure and Pawsey Supercomputing Centre run complex modelling and simulations
- the generation, analysis and retention of associated datasets are managed by the Australian Research Data Commons
- accelerator facilities such as the Heavy Ion Accelerators and Australian Centre for Neutron Scattering are used in the design and development of advanced materials for the manufacture of space products and services
- facilities such as 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			■	■			■	■

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
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 the above table as they are in development.

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 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, whilst 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. In the marine domain, there is need for increased observational capacity in coastal zones and on the ocean floor, with better integration of marine, freshwater and terrestrial monitoring. The need for greater capacity in atmospheric and air quality monitoring has been identified in both regional and urban areas. There is also significant potential for enhanced 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 infrastructures significant.

Increasingly, satellite data is being used in a wide range of observational applications, complementing ground-based and autonomous (eg 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 infrastructures could improve interconnections, drive efficiency and allow richer datasets to be collected.

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, driving efficiency and allowing richer datasets to be collected. As further discussed below (*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.

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 digital 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 through real-time information flows. 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 like the Australian Data Strategy to be released by the end of the year.

4.3 Physical collections and biobanking

Physical collections are a vital resource for research and underpin activities from health and medical research to ecological and agricultural fields. 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 or 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, creating an open-access infrastructure through development of unified sample management, metadata and access models and shared data infrastructure. Rapidly evolving analytical technologies (genomics, digitisation etc) are generating new opportunities for specimen and sample use and reuse that have not been previously possible and help manage the finite resources of biobanks.. Application of new technology means old samples are becoming valuable in new ways and 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. However, they are currently not coordinated or integrated. Medical and human biobanks are implemented at the state and territory level and involve complex ethics and regulatory frameworks.

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 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 along with 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.

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. 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 has identified the opportunity to develop broader 'research data commons' as larger, coordinated and optimised initiatives to address broader science and research priorities. Data commons provide shared and reusable analytics platforms, software and data tailored for specific communities. They are developed collaboratively with researchers and NRI. Existing data commons include the EcoCommons, 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 National Environmental Prediction System).

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 in addressing 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 support this outcome.

4.5 Bridging innovation gaps with translation NRI

To maximise social and economic dividends from the research sector, researchers require support across the entire innovation value chain. However, technology readiness levels (TRLs) beyond proof-of-concept typically lie outside the remit of the university research sector and 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-add 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 for 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 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 SMEs) 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*.

5. Building on a strong NRI foundation

The 2021 Roadmap process showed 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
- a 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.*
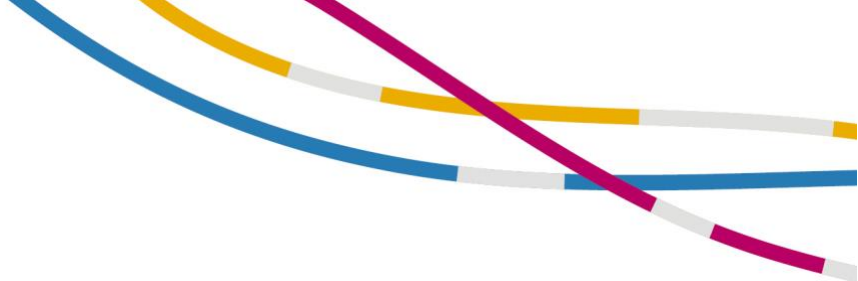
5.1 NRI Governance

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 (Commonwealth 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 has been confirmed again in 2021.

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. Adding to this complexity is the pace of technological advances and changes in research practice; government must invest in large-scale NRI within this environment. Roadmap consultations highlighted that planning should not happen in isolation every five years given the scope and complexity of research challenges and the need for a more responsive whole of ecosystem response to NRI development.

The 2015 Research Infrastructure Review (Clark Review) found that although multiple government departments and agencies play a role, there was no single body providing overall strategic direction for NRI investment[39].

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.

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. NRI staff manage, maintain, optimise and operate facilities, and a highly skilled workforce is needed to maximise the benefits of existing NRI investments, new technologies and applications. NRI staff support users and provide field-specific training to research communities more broadly. Due to the cross-cutting nature of NRI, staff play an important role in supporting collaboration, including

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

industry engagement and raising awareness of NRI capabilities. 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 facilities.

The attraction and retention of skilled staff can be challenging. This has resulted in both system-wide skills shortages (scientific 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[40].

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[41]. Formal qualifications in research infrastructure management could be developed for NRI leadership, similar to the Executive Masters in Research Infrastructure Management offered by the University of Milan. 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 facilities 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, whilst simultaneously lowering barriers to entry and helping develop new research and industry user communities.

5.3 Improvements in NRI impact

We recommend that the Expert NRI Advisory Group undertakes a review of 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.

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

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

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 and 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.

Projects currently funded under NCRIS also consider the ecosystem has sufficiently developed to the point that further value can be added through greater integration across functions and domains. Greater alignment and integration is discussed further in Chapter 5.5. 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 high performance computing capabilities.

There are opportunities to build on existing arrangements given the ongoing collaboration across the NRI network. 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.

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. 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 Australian, State and Territory Government 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 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 shifts in direction to respond effectively to future opportunities.

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, interaction, 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 across the NRI system. 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. It could drive researcher-centric outcomes, reducing barriers to access and support strategies for the development of the NRI workforce.

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 infrastructures focus on monitoring different quantities, researchers can leverage data from multiple infrastructures to gain greater insights.

- Computing and modelling

  - High performance computing allows researchers to model highly complex systems and perform advanced analysis of vast amounts of data.

- Datasets and collections

  - Datasets and collections are vital for all fields of research. Careful curation and improvements to the reliability, interoperability, accessibility and management of datasets and collections is crucial to ensure use and reuse of data.

- Measurement and characterisation

  - Measurement and characterisation analyse the properties of individual samples, including subatomic particles, molecules, materials and organisms. A wide variety of measurement and characterisation infrastructures are required to support measurements of different properties and spanning different size and time scales.

- Fabrication and prototyping

o Prototyping and pilot testing represent critical steps in transforming research ideas into tangible manufacturable products with real world impact. These infrastructures enable researchers and innovators to translate research outputs and manufacture materials to be used in research.

Such a function framework could help guide investments, strengthen the NRI network and drive greater collaboration within and between NRI. It could 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.

5.6 Indigenous knowledges and NRI

Indigenous knowledge has 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 people pursuing their self-determination aspirations. Aboriginal and Torres Strait Islander peoples' engagement with NRI is ongoing: the 2020 Investment Plan funded the Indigenous Data Network (IDN) to support Indigenous research capability. In partnership with the ARDC, but 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 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)[42] 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 people and NRI must be encouraged and underpinned by these principles. NRI should adopt the AIATSIS Code of Ethics definition of research, which includes *"all research that impacts on or is of particular significance to Aboriginal and Torres Strait Islander peoples, including the planning, collection, analysis and*

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[42] AIATSIS Code of Ethics for Aboriginal and Torres Strait Islander Research AIATSIS Code of Ethics for Aboriginal and Torres Strait Islander Research

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[43].

5.7 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 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 change to enable greater research impact and reach.

NRI encourages strong long-term industry and research partnerships, both domestically and internationally. NRI provides the tools and environment for researchers and industry professionals 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.

With a focus on research excellence, NRI can also fill gaps at the early stages of research translation and commercialisation, such as prototyping and testing. This normally falls outside the remit of university research and is too early to attract industry investment. NRI facilities also provide advanced manufacturing capabilities to support industry ventures or provide testing and quality assurance frameworks.

However, the Roadmap consultation process found that the industry sector has limited awareness of NRI, its benefits and how it 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.

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.

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

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[43] National Agreement on Closing the Gap, Australian Government.

accelerate university commercialisation outcomes, including through consideration of proposed options for the University Research Commercialisation Scheme[44].

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.

Scientific 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*: 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.

- *Raising the visibility and profile of NRI capabilities*: promotional activities like virtual open days and 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[45]).

- *Improvements to data linkage, storage, management and access*: creating more standardisation and streamlining of data management frameworks to facilitate industry engagement.

Government should consider the above opportunities to improve industry engagement in development of the 2022 Investment Plan. Based on consultation and analysis, a starting point could be the establishment of a collaboration and information intermediary between industry and NRI.

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[44] Department of Education, Skills and Employment, University Research Commercialisation Consultation paper, Australian Government, 2021.
[45] Department of Industry, Science, Energy and Resources, *New investment in Australia's quantum technology industry*, Australian Government, 2021.

This could be done through Industry Collaboration Facilitator roles (with links to existing government initiatives such as the Innovation Connections service) that connect across NRI facilities, establish networks and raise awareness of collaboration opportunities with industry.

5.8 Development of 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 strategy. The strategy will coordinate and integrate the national digital research infrastructure (NDRI) ecosystem to streamline access to data, computing and analysis needs for the research sector. This strategy will support researchers across all fields by not only maximising the data available, but also providing the computing resources and digital tools and expertise needed to make best use of the data. 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 NDRI strategy should be developed by Government over the next year with any immediate insights feeding into the 2022 Investment Plan.

Previous NRI Roadmaps have highlighted DRI as essential infrastructure. Significant investment stemming from the 2018 and 2020 Investment Plans led to the formation of the Australian Research Data Commons, upgrade 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:

- the continuing exponential growth in data acquisition and its associated storage challenges

- research trends include the growth in use of AI and machine learning

- the increasing use of DRI and HPC in non-traditional research areas such as genomics and bioinformatics

- the international push for open science which relies on integrated DRI and digitally skilled expertise.

The use of DRI is now routine and commonplace. The challenge for the 2021 Roadmap is identifying the NDRI that will support Australian researchers into the future. NDRI is defined as *"DRI components that are collectively managed and operated as shared 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."*

To address the growing data and computing needs of Australian researchers, maintain research excellence and remain competitive on the international stage, government should develop a strategy for an integrated NDRI ecosystem. The 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 cloud services.

The NDRI Strategy would 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. NRI that makes data accessible to researchers is critical to enable and encourage its use and reuse. Data generated through research activities within academia needs to be accessible to government, industry and others to maximise the use and reuse of the data.

Data needed for research is also increasingly generated, collected and stored outside of academia such as in government agencies and in the private sector and industry. Building on the reforms that will follow from the recently introduced National Data Availability and Transparency legislation[i], there is opportunity to explore the use of business, consumer and government administrative data to accelerate research and create opportunities for related value-add to business. In the case of access to sensitive data (such as that pertaining to health) there are regulatory and ethical factors 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. NRI has a key role in supporting the implementation and adoption of the NDRI Strategy and facilitating the participation of different stakeholder groups.

Data also needs to be discoverable and interoperable by users and preserved for long-term use. Applying existing international data principles such as FAIR (Findable, Accessible, Interoperable, Reusable) ensure that Australian research data is interoperable both domestically and internationally. Data generated, created, captured or stored 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 the landscape and beyond academia.

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

Data storage

Advances in computing and modelling, as well as research tools and instruments, have resulted in rapid growth of research data being generated. Current data storage capacity needs to be improved for both working data and longer-term retention as a national research asset. So much data is currently 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 what data needs to preserved, where and how the data is stored and who is responsible and funds the necessary data repositories.

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. Roadmap consultation process supported trust and identity being considered as fundamental research infrastructure. Currently this service is delivered by the Australian Access Federation (AAF) but it sits outside the NCRIS-funded NRI network. A system-wide approach to identity and access management using a common framework 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 (HPC)

Both of Australia's Tier-1 HPC facilities (NCI and Pawsey) have undergone major refreshes following the 2016 NRI Roadmap and the 2018 Investment Plan. Due to the rate of technological advancement and significant capital costs, there needs to be sustained and longer-term strategic planning and investment to keep pace and effectively exploit new hardware evolutions.

HPC is provided at the national level by two Tier-1 facilities, but access is limited due to strong demand and they are not always suited to the needs of researchers. Consideration should be given towards how NRI investment can increase capacity and resourcing of existing Tier-1 facilities. To address these user issues, current HPC access schemes, prioritisation and resourcing need to be improved to account for increasing and diverse researcher demands.

Some institutions have developed their own institutional Tier-2 HPC to address these issues, but these facilities are not always widely available. The increasing availability of commercial cloud computing might offer suitable alternatives. However, current commercial cloud offerings can be expensive and there may be issues regarding data protection and sovereignty.

Coordination, integration and further development of available Tier-2 HPC and commercial cloud computing to complement and support existing Tier-1 is needed to provide researchers with a more integrated ecosystem and different options. Universities and other research institutions that currently host computing infrastructure and commercial computing providers would be key players in developing such an integrated computing ecosystem. Such an ecosystem would likely be a mix or

hybrid model that includes traditional and cloud, commercial and non-commercial providers. Existing governance and access schemes would need to be considered in such a model.

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 to ensure efficient utilisation and to achieve best return on investment in hardware. Major advancements such as exascale computing will not be achievable without equivalent development of exascale-ready research software.

Due to its importance, research software needs to be considered as research infrastructure itself. There also needs to be a greater focus on the informatics services that underpin software assets to ensure researchers can find and access the research software that they need. This would ensure there is improved efficiencies and reduced duplication of efforts 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 in addition to conducting their research. For this reason, software infrastructure needs a dedicated workforce.

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 topic 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 computational, data management and analysis techniques.

Some research areas and institutions are already building data and computational expertise internally as an essential resource. There should be consideration of 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 must navigate multiple access schemes to access DRI in the right timeframe. DRI investments should drive an integrated ecosystem which provides seamless access to data and computing in a timely way, and potentially consider allocations under the one application or request.

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

6. Potential for step-change

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

To drive Australia's research growth 'landmark 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, and (where appropriate) supports Australia to lead the world in research and/or the ability to collaborate.

Roadmap consultations highlighted possibilities for landmark NRI investment. Examples include: the detection of gravitational waves, high-intensity lasers for fusion research, Australian Social Data Observatory (AuSDO), translational infrastructure for neurological disorders (Australian Brain Bank), nationally coordinated formulation, testing and early-stage manufacturing of therapeutics products for clinical trials (such as GMP grade manufacturing, mRNA therapeutics), membership of major international fundamental science projects (optical astronomy, particle physics).

The Expert Working Group has identified four initial areas for consideration which could focus NRI investment and deliver significant impact and step-changes 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 through access to cutting-edge infrastructure. The areas are:

- 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 activity will be required across these areas, 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 tackle future challenges*
>
> 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.

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. To manage this, key elements of computing processing power, data storage, expertise and researcher skills will be critical and require ecosystem-wide cooperation and planning.

Significant attention and investment in building Australian researchers' data, software and computing capability has the potential to deliver profound benefit and wide-reaching outcomes.

As discussed earlier in the Roadmap, a NDRI Strategy is necessary to coordinate and integrate Australia's diverse DRI landscape and streamline access for researchers and users. However, for this strategy to be effective, it must be accompanied by cooperation across the research ecosystem and committed government investment for Australia's DRI to keep pace with continued technological advancements.

It is vital that NDRI is ready to address and capitalise on impending and future major challenges and opportunities, namely exascale computing and increasingly big data. These will represent major NRI investment considerations and could include:

- the formulation of a clear Australian plan towards achieving exascale. Exascale computing could constitute a game-changer for the Australian research and innovation landscape

- 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, able to accommodate largescale datasets

- researcher training (data analysis and synthesis, AI/ML, data standards) to ensure that any data generated and stored will be FAIR, align with the 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 the next step-change in HPC 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*).

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 ground-breaking applications across improved agriculture and food production, precision medicine, the environment, biocontrol, and sustainable low-emission industrial processes[46]. Therefore, 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[47].

Synthetic biology research will benefit from the existing network of powerful NRI (Omics, HPC), but it 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 ground-breaking laboratory discoveries cannot be translated into real-world applications that will benefit the public. This investment would also align strongly with the

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[46] Australian Council of Learned Academies, *Synthetic Biology in Australia: An outlook to 2030*, Office of the Chief Scientist, Australian Government, 2018.
[47] Office of the Chief Scientist, *Occasional Paper: Synthetic Biology in Australia*, Australian Government, 2020.

broader research sector need for translation NRI discussed below (*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, the above investment will deliver world-class capacity in the development of new biological products and processes. This will place Australia at the forefront of this next biotechnology revolution and allow Australian industries to compete successfully on the international stage. The resulting research-innovation pipeline is also set to create new, disruptive bio-industries that will ensure future prosperity by underpinning a strong and sustainable bioeconomy that supports Australian net zero strategies and targets.

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 the Australian research and innovation sectors. Beyond ideation and discovery, much of the innovation value chain falls outside the traditional remit of university research, while still being 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 real-world products, establishing first run production and prototyping and finalising research commercialisation in Australia.

Focused investment to build a suite of translation NRI is necessary to empower researchers in validating their research outputs by demonstrating their commercial potential. This would in turn 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 which is necessary to transform 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 with international enterprises.

Investment in these areas would contribute significantly towards eliminating the research-innovation value chain gaps between research discoveries and tangible products and align the NRI system with preparation for commercialisation outcomes. This will in turn help create the business environment to encourage investment and support manufacturing jobs, and promote the industry-focus of the Australian science and technology system to boost productivity, scale and competitiveness. In this way, the wide-reaching potential of Australian research ingenuity could provide real-world solutions towards all challenges discussed in *Chapter 3: Research themes, challenges and NRI impact*.

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[48]. It will guide the process of adjusting to actual or expected changes in climate to reduce or avoid negative impacts, or exploit 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 system of NRI, geared towards collecting diverse climate and environmental data and predicting changes that might occur in the future. Australia's geographic features impose further unique demands that must be addressed by a suite of interconnected, world-leading NRI.

These demands mean that although some Australian NRI is already directed towards these concerns (and this issue is recognised as a theme in *Chapter 3: Research themes, challenges and NRI impact*), there is urgent need for a step-change in pace and scale of activities and necessity for unprecedented levels of integration and interconnectedness across this ecosystem. NRI investments 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[49]. Expanding, digitising, standardising nomenclature and DNA sequencing these collections and type specimens will create a crucial reference library for biodiversity and biosecurity and underpin ecosystem and climate modelling. This will enable the use of environmental DNA (eDNA) techniques to efficiently and effectively monitoring freshwater, marine and terrestrial ecosystems, providing a step-change in capability and ensuring Australia is well prepared for the coming decades

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[48] Department of Agriculture, Water and the Environment, *National Climate Resilience and Adaptation Strategy 2021-2025*, Australian Government, 2018.
[49] Deloitte Access Economics, *Cost benefit analysis of a mission to discover and document Australia's species*, 2021.

- better integration of environmental monitoring infrastructures, increased capacity in coastal and estuarial areas, freshwater systems and enhanced and integrated atmospheric monitoring in urban and regional areas. These investments will deliver comprehensive, world-leading environmental monitoring. Benefits include improved coastal management, management of pollutant sources, and improved responses to bushfires and dust storms

- foundational climate research and modelling to allow 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 Australia to better adapt to a changing climate

- 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, coastal and oceanic domains will create a world-class infrastructure, able to support decision making, adaptation planning, and intervention strategies.

A world-leading integrated NRI system will support researchers to engage with industry and government and will support Australia's plan for net zero emissions by 2050[50] and the National Climate Resilience and Adaptation Strategy[51]. The availability of information to better predict, manage and adapt to climate change, will enable assessment of national climate impacts, evaluation of adaptation progress, and continual improvement. The immense positive impact of meeting these objectives in the coming years will extend across many of the major challenges identified in *Chapter 3: Research themes, challenges and NRI impact*.

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[50] Department of Industry, Science, Energy and Resources, *Australia's long-term emissions reduction plan*, Australian Government, 2021.
[51] 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.

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

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
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 EWG 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 (University of Melbourne)

- Dr Michelle Perugini (Presagen)

- Dr Chris Roberts AO (Atmo Biosciences)

- Professor Liz Sonenberg (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 EWG is 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 and Department of Agriculture, Water and the Environment. The members of the Taskforce include:

Ms Margaret Leggett, Ms Danielle Donegan, Ms Bernadette Kelly, Ms Mary Mulcahy, Dr Lee Alissandratos, Ms Grace Campbell, Ms Michelle Chatelin, Ms Mariana Dias Martins, Mr Jason Finley, Mr Nick Fishlock, Ms Cornelia (Nellie) Herbert, Dr Elaaf Mohamed, Ms Stephanie Priestley, 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 EWG and Taskforce members undertook extensive consultation using a variety of virtual platforms, including a survey, a series of workshops, and two 'Ideas Jam' time-limited forums designed to promote the sharing of ideas.
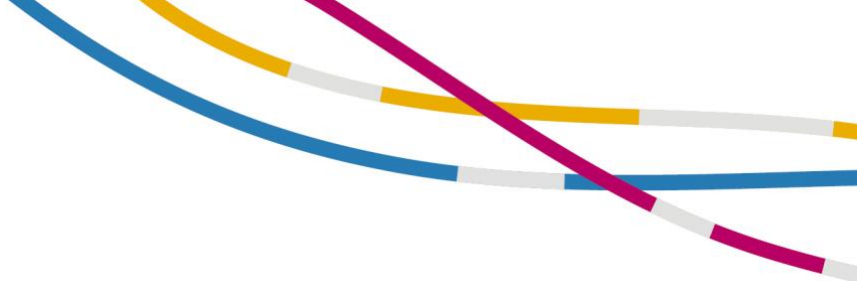
Friday: The Creative Intelligence Collective coordinated consultations through a public website portal and email registration. Over 1000 people registered to receive email updates for consultation events and updates on the development of the Roadmap.

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.

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

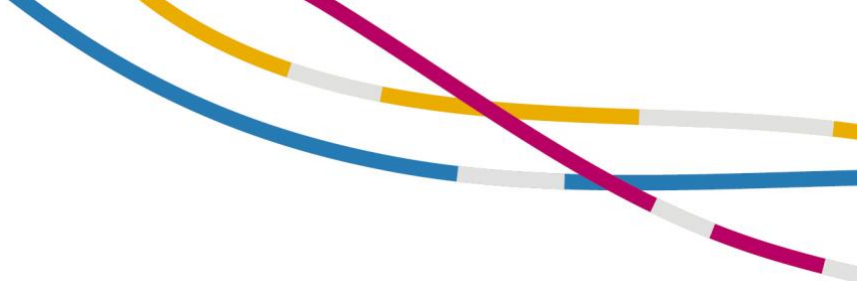The EWG and Taskforce members consulted broadly with NRI stakeholders, including:

- AARNet
- Australian Access Federation
- Australian Government Interdepartmental Committee for the 2021 NRI Roadmap
- Australian Learned Academies
- Cicada Innovations
- CSIRO
- Forum of Australian Chief Scientists
- Group of Eight
- Innovation, Science and Economic Development Canada
- 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
- NCRIS Directors and Chairs
- State and Territory government and Chief Scientists
- United Kingdom Research Infrastructure (UKRI)
- 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
AAF	Australian Access Federation
AAHL	Australian Animal Health Laboratory
AAL	Astronomy Australia Limited
AAO	Australian Astronomical Observatory
ACCESS	Australian Community Climate and Earth System Simulator
ACDP	Australian Centre for Disease Preparedness
ACNS	Australian Centre for Neutron Scattering
ACOLA	Australian Council of Learned Academies
ADA	Australian Data Archive
AI	Artificial intelligence
AIATSIS	Australian Institute of Aboriginal and Torres Strait Islander Studies
AIMS	Australian Institute of Marine Science
AITC	Advanced Instrumentation and Technology Centre
ALA	Atlas of Living Australia
AMMRF	Australian Microscopy and Microanalysis Research Facility
ANDS	Australian National Data Service
ANFF	Australian National Fabrication Facility
ANSTO	Australian Nuclear Science and Technology Organisation
APPF	Australian Plant Phenomics Facility
ARC	Australian Research Council
ARDC	Australian Research Data Commons
AREN	Australian Research and Education Network
ASKAP	Australian Square Kilometre Array Pathfinder

Acronym	Description
AURIN	Australian Urban Research Infrastructure Network
BPA	BioPlatforms Australia
CAS	Centre for Accelerator Science
CRC	Cooperative Research Centre
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DNA	Deoxyribonucleic acid
EBI	European Bioinformatics Institute
EMBL	European Molecular Biology Laboratory
EU	European Union
EWG	Expert Working Group
FAIR	Findable, accessible, interoperable and reusable
GBI	Global Bioimaging
GMT	Giant Magellan Telescope
GRACE	Gravity Recovery and Climate Experiment
HASS	Humanities, Arts and Social Sciences
HCI	High Content Imaging
HIA	Heavy Ion Accelerators
HPC	High performance computing
IMOS	Integrated Marine Observing System
IODP	International Ocean Discovery Program
LIGO	Laser Interferometer Gravitational-Wave Observatory
MASSIVE	Multi-modal Australian ScienceS Imaging and Visualisation Environment
ML	Machine learning
MicroAU	Microscopy Australia
MNF	Marine National Facility
MRFF	Medical Research Future Fund

Acronym	Description
MRI	Magnetic Resonance Imaging
MWA	Murchison Widefield Array
NBF	National Biologics Facility
NCI	National Computational Infrastructure
NCRIS	National Collaborative Research Infrastructure Strategy
NDRI	National Digital Research Infrastructure
NDF	National Deuteration Facility
NIF	National Imaging Facility
PA	Phenomics Australia
Pawsey	Pawsey Supercomputing Centre
PET	Positron Emission Tomography
PHRN	Population Health Research Network
RNA	Ribonucleic acid
SKA	Square Kilometre Array
TERN	Terrestrial Ecosystem Research Network
TIA	Therapeutic Innovation Australia
UK	United Kingdom
USA	United States of America