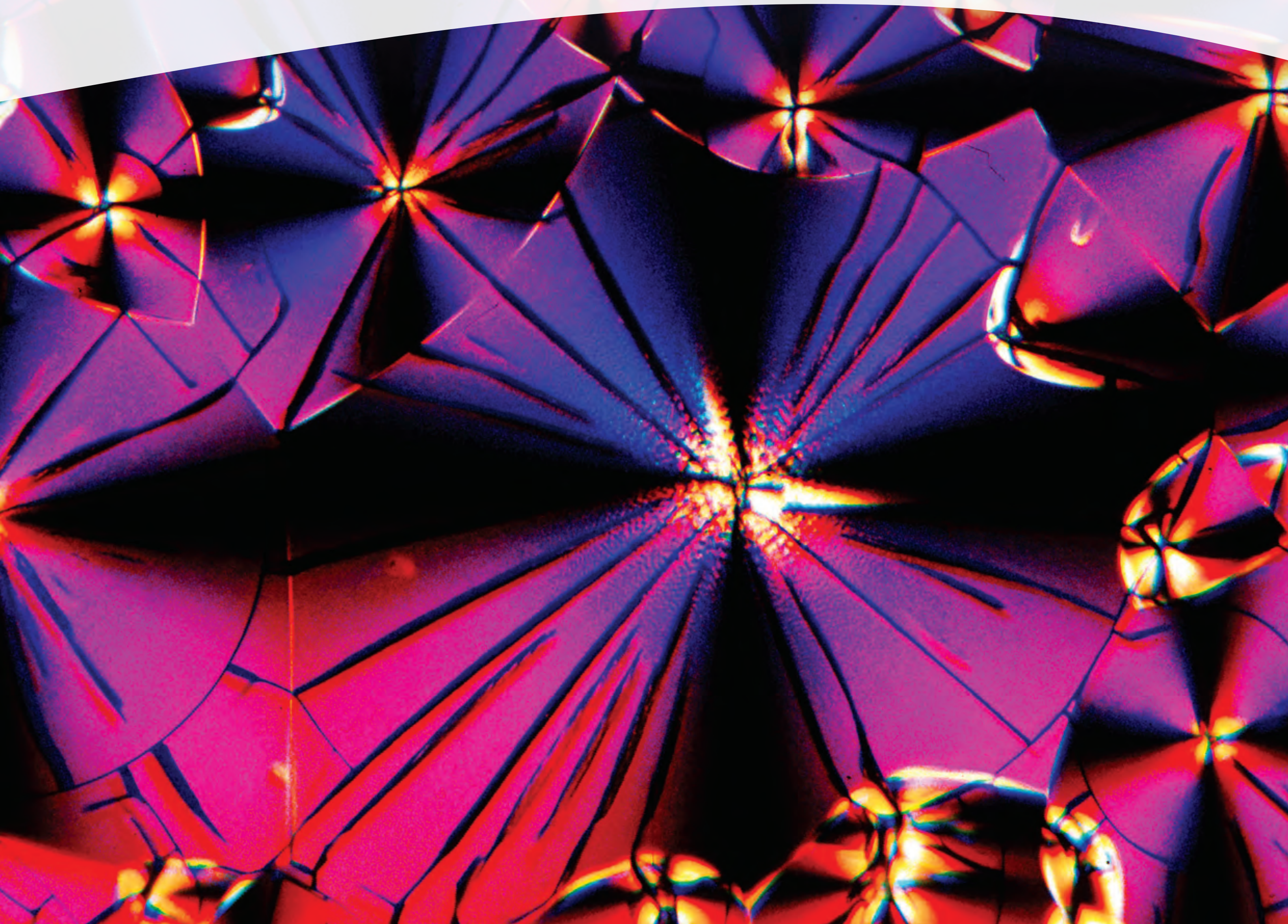
Australian Academy of Science

NATIONAL COMMITTEE FOR CHEMISTRY | AUSTRALIAN ACADEMY OF SCIENCE | FEBRUARY 2016

Chemistry for a better life

The decadal plan for Australian chemistry 2016–25



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Prepared by the Decadal Plan Working Group
on behalf of the National Committee for Chemistry

Cover image: A photo-micro-graph of Biotin (Vitamin H).
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Foreword

Chemistry as a discipline has been and remains a significant contributor to the wealth, prosperity and health of the human species. Over the last 5,000 years, chemistry—more than any other discipline and practice—has made our global civilisation and prosperity possible.

But now our world is changing in extraordinary ways, bringing with it a host of opportunities and challenges for science and society. The principal question is: how can we support an ever increasing population of highly connected citizens, most of whom aspire to a higher degree of material wealth, increased life expectancy and global mobility, when Earth has only finite resources and energy reserves?

Globally, chemistry will remain indispensable in positioning and responding to these opportunities and challenges. Australia is a very small but determined player—contributing both to chemistry as a science and discipline—and is home to a significant chemical industry. It needs to be positioned to take advantage of unprecedented global growth where chemistry is an enabler of economic, social and environmental prosperity. Our vision for chemistry in 21st century Australia is simple:

Chemistry for a better life—inventing what matters

This vision integrates and addresses the new global opportunities for, and challenges to, humanity, and Australia's own challenges for members of the chemistry community engaged in research, teaching and industry. Each of these areas undertakes important work to improve and contribute to Australia's prosperity.

The pathway presented in this decadal plan is the result of extensive and detailed consultation with stakeholders to find the common ground that exists to support the discipline and practice of chemistry to benefit all Australians. It is primarily a bottom-up, community-driven document, aiming to guide investment and effort in chemistry research, education, industry and infrastructure.

In essence though, this plan is for the children who are just six years old today. These children will be deciding whether to study Year 12 chemistry in 2025. They will be deciding whether chemistry is an exciting scientific discipline, whether it offers real intellectual challenges, whether it offers sustainable jobs and rewarding career pathways and whether the pursuit of chemistry will enable them to have a real impact on the world around them. These children need to understand that chemistry is important to the lives of Australians: that it is an essential part of the solutions to global problems such as sustainable food, potable water, advanced medical care and renewable energy. We hope you will support the strategies and vision outlined in this plan, which will ensure chemistry is still the central science in 2025.

Professor Andrew Holmes AM PresAA FRS FTSE
President, Australian Academy of Science
February 2016

Medicinal chemistry—vital for better health for all Australians.
CREDIT: ISTOCKPHOTO/ FANGXIANUO

Executive summary

Chemistry is the science of molecules: the basic building blocks of matter. Chemists have shown that all the substances around us, Earth and indeed the universe as a whole, are composed of 92 building blocks or elements.[1] In fact, just seven of these fundamental chemical elements are responsible for more than 99% of the world around us.

Chemistry is the central science. In sharp contrast to other major science disciplines such as physics, mathematics and biology, chemistry is the only 'fundamental' science that has a specific industry attached to it. It spans basic science and education through to advanced manufacturing, and is the most significant contributor to the wealth, prosperity and health of the human species. Over the last 5,000 years it has been chemistry, more than any other discipline, which has made our global civilisation possible. In the 21st century, chemistry will contribute to such innovations as energy efficient LEDs, solar cells, electric vehicle batteries, water desalination technology, and biodiagnostics—as well as drive discoveries for the aeronautical, defence, agricultural, health and medical sectors.

In Australia the chemical industry employs more than 60,000 people[2], and together with the other physical sciences and mathematics it contributes $145 billion dollars annually to the Australian economy.[3] Amongst the physical sciences, chemistry remains the largest single scientific discipline.

The Decadal Plan for Chemistry comes at a crucial time for Australia. The nation's economy needs to transition from a mining boom focus to a balanced, forward-focused manufacturing base. Australia needs to re-invigorate key areas of the manufacturing sector, and chemistry is one of the most promising areas for investment. To continue to have impact and relevance over the next ten years, Australia needs:

- a vigorous chemistry education system
- an internationally competitive R&D sector
- a cohesive, well-networked marketplace for new products.

1 There are in addition some 15 artificial but unstable elements that have been synthesised.

2 PACIA_strategic_directions_WEB.pdf

3 'The Importance of the Advanced Physical and Mathematical Sciences to the Australian Economy', Australian Academy of Science, Canberra, 2015

Australia has the capacity to discover and develop new chemical products and has the experience, expertise and resources to match or exceed its Asian neighbours in design, innovation and product quality.

Meeting the goals of the decadal plan will help advance Australia's move towards more sophisticated, value-adding products and will drive expansion of the manufacturing sector, which is crucial for the evolution of other emerging industries such as the nascent biotechnology and biomedical devices sectors.

The vision of the decadal plan is:

Chemistry for a better life—inventing what matters

A vigorous and exciting chemistry education is essential for the next generation of scientists, entrepreneurs and inventors. A great example is the Wii Gaay Project for Indigenous children. CREDIT: WII GAAY PROJECT

Purpose of the decadal plan

It is more than 20 years since the last analysis of the chemistry discipline was undertaken.[4] The decadal plan for the 10 years to 2025 has been developed to ensure a coordinated effort across the discipline and to maximise the benefit of chemistry for all Australians—leading to improved economic and social prosperity, greater wealth creation and better integration with the long-term sustainability needs of the natural environment.

4 Spurling, T. H.; Black, D. S.; Larkins, F. L.; Robinson, T. R. T.; Savage, G. P., Chemistry—A Vision for Australia. In Australian Government Publishing Service, 1993; pp 1–79. See also: Upstill, G.; Jones, A. J.; Spurling, T.; Simpson, G., Innovation Strategies for the Australian Chemical Industry. Journal of Business Chemistry 2006, 3 (3), 9–25

Australia relies on chemistry to maintain its safe clean water supplies. Recycling will be essential for sustaining this resource on the driest continent.
CREDIT: ISTOCKPHOTO/PAMSPIX

The decadal plan is the first step in advancing Australia's most important, value-adding manufacturing sector. It identifies the key challenges, barriers and opportunities for Australia in the 21st century and proposes solutions that can help Australia reach its potential as a world class international manufacturing hub.

The decadal plan was formulated in collaboration and consultation with chemistry's key stakeholder sectors, including:

- primary and secondary education
- tertiary education and research
- government research providers
- government
- industry.

In an increasingly competitive global industry, the decadal plan will guide Australian investment and activity to add to the global body of chemistry knowledge. It will efficiently deliver knowledge and improved products and services for national and international markets.

Winds of change—opportunities and threats for the global and Australian chemistry industry

The plan identifies significant trends, challenges and opportunities.

Global megatrends, threats and risks that present both major challenges and new opportunities for the industry include:

- population growth and demographic shifts
- economic power shifts
- climate change, resource scarcity and declining sustainability
- technology-driven economic change.

Ten 'Grand Challenges' for chemistry are:

1. increasing agricultural productivity
2. conserving scarce natural resources through alternative materials and new processes to extract valuable materials from untapped sources
3. converting biomass feedstock through the development of bio refineries, using different types of biomass to provide energy, fuel and a range of chemicals with zero waste
4. developing diagnostics for human health to enable earlier diagnosis and improved disease monitoring
5. improving drinking water quality through new technologies
6. synthesising new drugs to transform drug discovery, that can deliver new therapies more efficiently and effectively
7. improving energy conversion and storage
8. harnessing nuclear energy safely and efficiently by developing fission and investigating fusion technologies
9. improving solar energy technology, yielding more cost efficient processes and developing the next generation of solar cells
10. designing sustainable products that take into account the entire life cycle of a product during initial design decisions to preserve valuable resources.

The consultation process revealed:

- international commercial and social trends, threats and challenges to the industry
- impediments to interactions between the sectors
- sector-specific and sector-spanning issues that are impeding efficiency

- current and specific requirements that need to be addressed to facilitate growth

Barriers to success

School education

- School students are forced to make uninformed career choices because teachers, parents and students have insufficient knowledge about the relevance and benefits of chemistry to society and the career opportunities it presents.
- Many secondary school chemistry teachers and primary school teachers do not have sufficient domain expertise in chemistry to provide passionate teaching and facilitate inspired learning.
- Students can deselect chemistry at school and yet still enter science or chemistry undergraduate degrees, meaning the higher education sector has to provide bridging courses to students.
- There is often limited infrastructure and capacity to provide practical chemistry experience in schools in disadvantaged, remote and regional locations, which limits access to chemistry education and the quality of teaching.

Higher education

- The number of students electing to do STEM subjects at school, including chemistry, is declining.
- Alternative chemistry pathways through technical schools and TAFE receive little funding.
- There are serious issues facing smaller regional universities due to the 'flight' of good school leavers to the capital city universities. This is resulting in a wide disparity in quality of chemistry courses and graduates across Australia.
- There are no mandatory minimum entry requirements for chemistry courses at universities.
- There is no agreed and uniform university curriculum. This makes it difficult for current and future secondary school teachers to lift the standard of school chemistry teaching.
- Staff to student ratios are becoming increasingly unfavourable, leading to poorer teaching outcomes.

Academic research

- Due to the heavy reliance on ARC funding, the sector focuses on 'run of the mill' research and does not embark on more ambitious and higher risk research that could be the basis for future high-end innovation in Australian industry.
- Young researchers in the sector are disenchanted because of poor career prospects.
- The focus on ARC research funding is a disadvantage for women in the academic sector, and does not support greater gender balance in higher level academic positions.
- The lack of funding options for chemistry outside the ARC, the low chance of funding, and the substantial time burden associated with applying for ARC grants lead to low research efficiency and productivity in chemistry.
- Universities lack the resources and capabilities to demonstrate the value of their research to industry.
- Chemistry departments have a poor track record of translating their research into new products via start-ups or industry collaboration.
- Chemistry researchers are not rewarded for interaction with industry and believe such interactions actually penalise their careers.

Government research

- Disenchantment within a large proportion of government research organisations means highflyers leave for overseas positions, reducing Australia's innovation capability.
- There is poor delineation between basic research and strategic research in government research agencies and there is unnecessary competition with the academic sector and duplication of effort across agencies and universities.
- Schedules for delivery of research to industry are 'unviable' because of the other management and administrative workload responsibilities that fall to researchers.
- There is duplication of agencies for commercialisation and funding, leading to reduced research efficiency.

National large research facilities

- There is concern within the chemistry research community about future funding and upgrading of the main large research facilities and related infrastructure.
- There is concern about the availability of funds to undertake research at these facilities.

Australian chemical industry

- There is low awareness within the industry of the potential of patentable innovations to drive industry competitiveness in a global, carbon-constrained environment.
- There is poor understanding within the industry of the capacities and capabilities of Australian research providers.
- Small industry companies are disadvantaged in their interactions with R&D providers.

Industry competitiveness

- There is sub-optimal 'value chain thinking' among chemistry stakeholders and limited awareness of the various ways issues in one sector can negatively or positively impact performance in other sectors.
- Although government is an essential contributor to the chemistry sector, government does not recognise its importance to the productivity of each sector and to performance of the chemistry industry as a whole.
- Key stakeholders agree that translation of research outcomes into products, processes and services is inadequate and needs to be addressed as a matter of priority on a much bigger scale than current government policy envisages.

RAISE CHEMISTRY KNOWLEDGE AND SKILLS

IMPROVE THE CAPABILITIES OF THE RESEARCH SECTOR

RAISE THE LEVEL OF INNOVATION EFFICIENCY AND ENHANCE THE CAPACITY OF INDUSTRY TO INNOVATE

- Poor policy and regulatory development, attributed to the very low science literacy of policy makers and the general public, has a strongly negative impact on the competitiveness of all sectors of the industry and its 'customer' industries.

The general public

- Australia has a very low proportion of citizens who are scientifically literate, with a background in science or technology (STEM subjects). There are few leaders able to understand the implications of technical innovation.
- Chemistry has a poor image in the population, and this perception is developed at a very young age.

Plan for success: the Decadal Plan for Chemistry strategic goals

The decadal plan sets five strategic goals:

- **Strategic goal 1**: Raise chemistry knowledge and skills
- **Strategic goal 2**: Improve the capabilities of the research sector
- **Strategic goal 3**: Raise the level of innovation efficiency and enhance the capacity of industry to innovate
- **Strategic goal 4**: Improve the image of chemistry
- **Strategic goal 5**: Implement the decadal plan

Recommendations

The decadal plan makes five key recommendations:

- **Recommendation 1: Australia continues to invest in the vitality and strength of its chemistry sector**, which underpins the vast majority of the manufacturing sector of the Australian economy.
- **Recommendation 2: The Australian chemistry community seeks stronger differentiation and focus of both its research and commercial products**. This will enable the Australian industry to be competitive in the global market through different and better outputs including niche products for special Australian market needs, but also through distinctive and unique manufacturing processes and higher quality services. Australia must differentiate on quality, but must also be pro-active in seeking new areas and markets to develop.
- **Recommendation 3: The Australian Government accepts the strategies outlined in the decadal plan**. These strategies will help to create a more connected and cohesive chemistry community, and will support the development of chemistry as Australia's most significant value-adding industry.
- **Recommendation 4: The Australian Government, the Australian chemical industry, the large R&D sector and the broad chemistry education system, together establish a Decadal Plan Implementation Committee** that has agreed terms of reference, the authority to develop appropriate budgets and sufficient funding to oversee the implementation of the draft strategies.
- **Recommendation 5: As part of its charter, the Decadal Plan Implementation Committee undergoes a mid-term review of its progress in 2020**. The review committee should consist of stakeholders from across the sector as well as external Government representatives.

The way forward

Australia must continue to invest in maintaining the vitality and strength of its chemistry sector. The decadal plan offers the tools to the leaders of the chemistry stakeholder sectors to make this possible.

Chapter I
Background and introduction

The proposal to develop a decadal plan was an initiative of the Australian Academy of Science. The proposal was included in the terms of reference for the Academy's National Committee for Chemistry in mid 2013 (Appendix 1).

The terms of reference for the Decadal Working Group (Appendix 2) were to:

- consult with all sectors of the chemistry value chain, including the primary and secondary school sectors, higher education sector, the research provider sector, industry regulators, industry and government policy makers.
- provide strategic science policy advice to the Academy for input into science policy statements, and (with the approval of the Executive Committee of Council) to the Australian Government and other Australian organisations.
- connect the Academy to chemical science and scientists in Australia.
- ensure Australia has a voice and a role in the global development of chemistry.
- facilitate Academy links to all sectors of the chemistry value chain, in order to raise the relevance and viability of chemical science and to promote development of the discipline.
- facilitate the alignment of Australian chemical science to the global chemical science community and global scientific goals.
- produce a decadal plan for chemistry in Australia.
- produce an implementation plan upon acceptance of the strategic direction of the decadal plan.

The process to create the decadal plan, including development of strategic options, implementation options and recommendations, followed a number of steps (Figure 1).

A potential list of working group members was drawn up in January 2014 and the final composition of the working group was finalised in March 2014. The working group included major stakeholders across Australia, different subsets and specialisations within the field and included representation from industry through PACIA and from government research

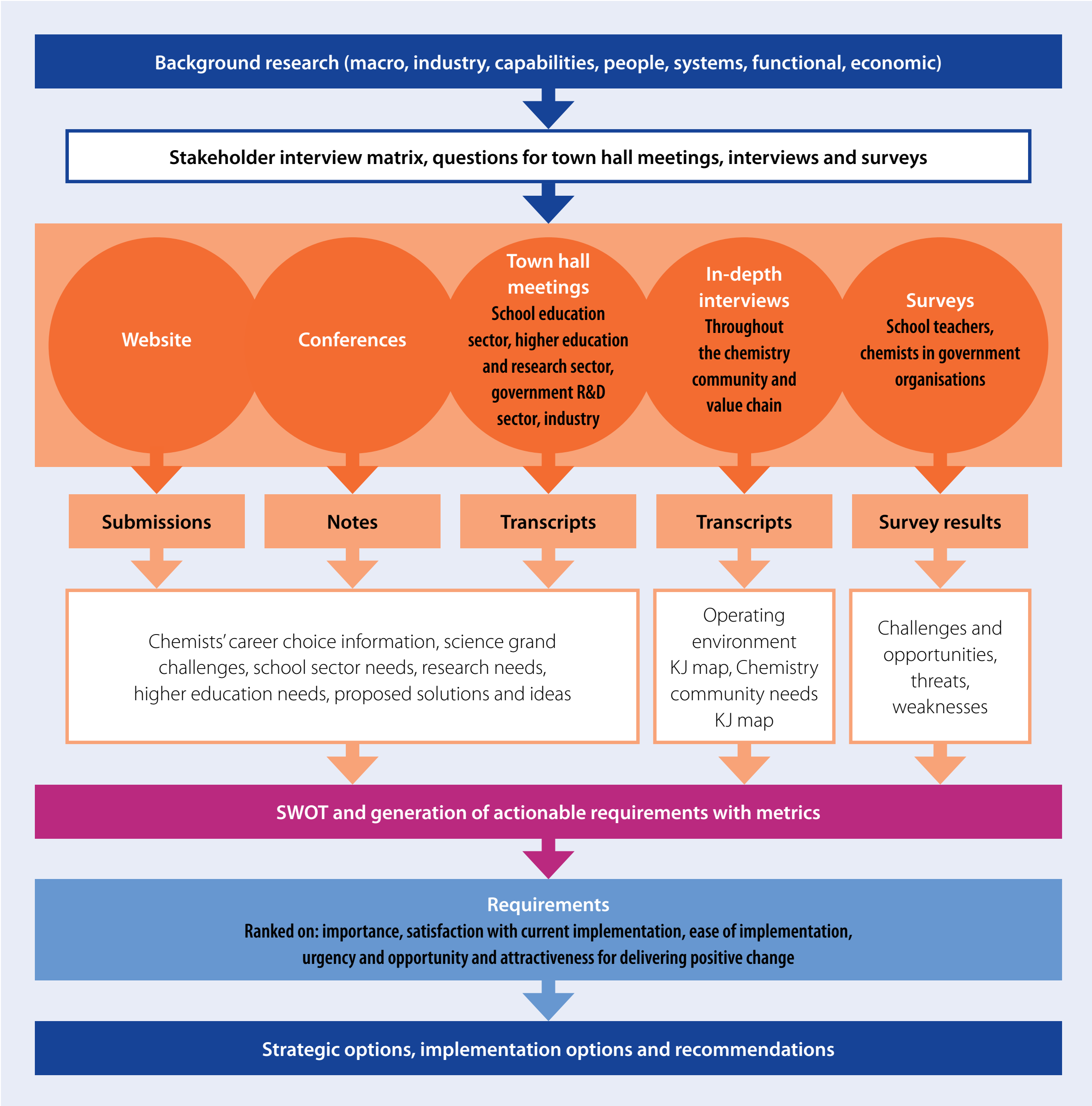
More than 40% of the world's food supply depends on the production of chemical fertilisers. CREDIT: CSIRO/GREGORY HEATH

providers such as CSIRO, as well as secondary school representation (Appendix 3) and universities offering chemistry degrees (Appendix 4).

The Decadal Plan Working Group employed a general business planning approach to its stakeholder consultation, analysis and strategic planning, and undertook an extensive program of research and consultation to understand the chemistry value chain in Australia, its challenges and requirements and to rank them according to importance and priority (Appendices 5, 6, 7, 8 and 9).

This analysis was used to develop the strategic directions, goals and recommendations presented in this decadal plan. The goals identified were then used as the key inputs for the development of a high level implementation plan.

Figure 1: Decadal Plan Development Process



Chapter II
Why chemistry matters

Chemistry is the science of molecules: the basic building blocks of matter. Chemists have shown that all the substances around us, Earth and indeed the universe as a whole, are composed of 92 building blocks or elements.[1] In fact, just seven of these fundamental chemical elements are responsible for more than 99% of the world around us.

In sharp contrast to other major science disciplines such as physics, mathematics and biology, chemistry is the only 'fundamental' science that has a specific industry attached to it.

The importance of the discipline of chemistry

Chemistry as a discipline has been and remains a significant contributor to the wealth, prosperity and health of the human species. Over the last 5,000 years, it is chemistry, more than any other discipline, which has made our global civilisation possible (Table 1).

The TV documentary series 'The Ascent of Man'[2] charted the correlation in human prosperity through the chemical discoveries that led to technological revolutions in our past—from Stone Age, to Bronze Age to Iron Age and hence to steel, plastics, petroleum, silicon, DNA and most recently graphene.

Early civilisations learned how to extract simple metals and to process them, which enabled military and eventually economic superiority. Likewise the civilisations that discovered gunpowder gained ascendancy in many areas of the globe. Innovations such as the development of specific cements, mortars and, later on, concrete, glass and plastic allowed urbanisation on a massive scale and larger, longer-lasting buildings. The industrial revolution was enabled by the rapid improvements in understanding combustion and thermodynamics of fossil fuels and this led to global power shifts to countries which were able to implement these innovations on an industrial scale.

More than 70% of Australians live in urbanised environments. Australia's chemistry industry provides advanced energy saving materials and directly supports skilled construction jobs across our cities.

In the 21st century, chemistry will continue to define the directions of technological change. For example chemical research and development will contribute to energy efficient LEDs, solar cells, electric vehicle batteries, water desalination technology, biodiagnostics, advanced materials for durable clothing, aerospace, defence, agriculture and health and medicine.

The global chemicals industry

In 2014, the global chemicals industry contributed 4.9% of global GDP.[3] When the 2006 RACI Chemistry business report was released, the global chemical industry had revenue of US$1.7 trillion. A decade later, the gross revenue is US$5.2 trillion.[4] That corresponds to US$800 for every man, woman and child on the planet.

The largest market for chemical industry outputs is now Asia—where the share of the global chemical industry revenue grew from 40.9% to 54.2% over the same period.

1 There are in addition some 15 artificial but unstable elements that have been synthesised.
2 Jacob Bronowski, The Ascent of Man, BBC documentary series 1975

3 Cefic Chemdata International – The European Chemical Industry Council (2014) report
4 http://www.statista.com/statistics/302081/revenue-of-global-chemical-industry/

Table 1: A few of the many chemistry inventions during human history

Period	Discovery	Impact
5000 BC	Discovery of glass probably as side product from copper or tin smelting	Used in architecture, cups and jewellery and nowadays in all transport and buildings
Copper Age 5000–3500 BC	Discovery of copper	First metal tools produced
Bronze Age 4500 BC	Alloying of copper and tin produced harder metal: bronze	Trading of bronze and tools—technology transfer, stronger weapons
Iron Age 1200 BC	Hot smelting and furnaces needed for recovering and working the metal	Superior weapons to earlier bronze weapons
	Invention of concrete/mortar	Urban development
	Invention of bitumen	Allowed proper roads to be built
	Invention of gunpowder	Enabled guns and cannons to be developed
1500–1990	Discovery of painkillers and anaesthetics: opium, ether, chloroform, laughing gas, morphine	Revolutionised medicine and made surgery possible
1791 Lavoisier, Scheel & Priestley	Discovery of oxygen—first element to be isolated since the natural occurring ones known since Roman times	Allowed the nature of combustion to be clarified. Metabolism in living creatures shown to be a type of combustion
1800 Alessandro Volta	Invention of the electrical battery	Enabled portable electrical supply
1804–1811 Humphrey Davy	Discovery of seven elements using electrolysis	Established the link between electricity and chemistry
1843 Charles Goodyear	Development of vulcanised rubber after a lifetime of persistence	Led to pneumatic tyres and polymer industry
1856 Charles Perkins	Development of the first purple dye, mauveine, followed by a series of aniline based dyes	Dye production drives organic chemistry and leads to establishment of some of the world's biggest companies: BASF, Agfa and Bayer in Germany
1871 Dmitri Mendeleev	Development of a periodic table of the elements based on similarity and recurrence of properties	Recognition that all substances are made from combinations of indivisible building blocks called the chemical elements
1874 Carl von Linde	Invention of the first refrigeration cycle using dimethyl ether and later ammonia	Led to widespread industrial production of liquefied gases. Allowed storage of foods and transportation across the globe
Marie and Pierre Curie	Discovery of unstable, radioactive elements radium and polonium	X-ray imaging, nuclear power, radiotherapy in medicine
1907 Leo Baekeland	Invention of first artificial plastic, bakelite	Revolutionised the manufacture of household goods
1909 Fritz Haber & Carl Bosch	Invention of chemical process to make ammonia, making it possible to produce large amounts of fertiliser	140 million tonnes currently produced annually. Quadrupled agricultural productivity. Uses 3–5% of world's natural gas annually
1938 Wallace Carothers (du Pont)	Invention of Nylon 66	Revolutionised garments and clothing, then extended to moulded parts in furniture, flooring
1939 Paul Muller (DDT) **1970** John Franz (Glyphosate)	Discovery of pesticides and herbicides	Major driver for increased food production and productivity of arable land. Yields four-fold return to farmers. Used with transgenic crops
1953 Crick, Watson & Franklin	Discovery of the structure and mechanism of DNA	Explanation for heredity, diseases and how cells function and life evolves
1983 Kerry Mullis	Discovery of polymerase chain reaction (PCR), which enables the rapid scale up of a single strand or small amount of DNA	Revolutionised forensics, genetics testing, transgenic implantation
1985 Harold Kroto, Richard Smalley, Robert Curl	Discovery of a completely new form of the element carbon. Lighter, harder and stronger than most existing materials	Revolutionised energy efficient materials design from bicycles to aircraft

Australia is the lucky country but needs to do more with its unique mineral resources. Australian governments can incentivise more value-add to our mineral products and drive new jobs in chemical manufacturing. CREDIT: GRAEME CHURCHARD VIA FLICKR CC BY 2.0

Combined revenues for the top 50 global chemical firms increased 1.7% to US$980.5 billion in 2013.[5] The top 10 chemical companies in the world had a turnover of US$429 billion in 2014.

Innovation in the global chemical industry is mostly driven by the innovation plans of the largest companies and by the innovation policies of the major production regions and countries, such as the EU, the USA, and some of the major Asian countries. Countries with the highest innovation intensity are the USA, China, the EU, Japan and Switzerland. China and India are emerging as large investors in chemistry R&D.

Many of the large chemical companies re-invest a substantial proportion of their sales revenue in their R&D projects and facilities. Some of these are increasingly diversified and have relocated closer to their major customer markets or manufacturing bases. As a result, many international chemical companies have been moving their R&D capabilities out of Australia, leaving only customer service and some minor manufacturing capacity in Australia.

Australia as a developed country should be reducing its exports of raw mineral products. The easy option of exporting raw minerals has led to a decline in innovation. As a result, the Australian chemical industry requires resourcing and incentives to drive more downstream value-add to the mining of the country's natural ores and mineral deposits. For example, lowering the tax rates on minerals and other raw inputs sold internally within Australia can help make the establishment of local chemical manufacturing more economic. Full taxes would be imposed only on internationally exported products. Furthermore, domestic reservation of key inputs such as natural gas can help to stimulate innovation across the sector. The US has done this with its shale gas deposits and, as a result of corralling some of its gas supply for domestic use at competitive prices, there has been a rapid resurgence of the US chemical industry. The lower cost of energy has made its manufacturing costs competitive with Asia.

5 http://cen.acs.org/articles/92/i30/CENs-Global-Top-50-Chemical.html

One of many challenges is to meet energy demands for heating, cooling, transport and technology.

Chapter III
Grand challenges

Winds of change—global megatrends and threats

Our world is changing in extraordinary ways. For the first time in history, humans now occupy most of the habitable regions of this planet. This has led to the emergence of the first, true, global economy. However, this unique situation brings with it a host of challenges for science and society. The principal question of course is: how can we support an ever increasing population of highly connected citizens, most of whom aspire to a higher degree of material wealth, increased life expectancy and greater global mobility, when Earth has only finite resources and energy reserves?

There are at least four emerging 'megatrends' that are going to strongly affect our lives over the coming decades (Table 2). These trends are complex; they interact with each other but their growing importance is undeniable. There is wide agreement globally among major consulting companies, business and government advisors, and within the major powerhouses of the global economy, that these trends are real and that research and better science are required to enable adaptation, regardless of which one of these trends in the end becomes the major driver for global change over the next 20 to 30 years.

Table 2: Megatrends, their impacts and rising challenges

Megatrends to 2050	Impacts	Rising challenges
Demographic shifts • Population growth • Population age profile shifts • Increased urbanisation • Rise of individuality • Rise of middle class in developing countries	9.7 billion people by 2050 21% of the population aged over 65 years 75% of the population living in urban environments Megacities in coastal areas and megatransport corridors 40% of Gen Y (people born in the 1980s and 1990s) living in India and China Increasing demand for consumer goods and services Uncertain labour opportunities for both young and older people Increasing migration	Increased greenhouse gas generation Management of water Waste management Transport and housing infrastructure and processes Power generation and distribution to meet demand for heating, cooling, transport and technology Access to education Epidemics and human health Underemployment (especially of youth and older people)
Technology as an enabling force • Digitisation • Interconnected technology • Pervasive technology • Convergence of technology	Increasing use of electronic equipment by individuals, businesses, transport and government Collection of big data for analysis and solution development for business, cultural and social benefits. Convergence of competition Creation of a third, social economy	Shortage of rare chemicals used in electronics Electronic and chemical waste Faster economic cycles due to faster communication and technology High power demands to maintain technology functionality Cyber security risks

Megatrends to 2050	Impacts	Rising challenges
Economic power shifts • Economic power shift to developing countries • Multipolar world	Trade liberalisation and free trade agreements Capital flow to economically powerful countries Developing countries become consumer countries with an expanding middle class Innovation powerhouse countries will be increasingly in Asia, with more established economies facing competition	Associated shift in political and military power Potential risks of instability Equitable distribution of wealth Potential new economic, political and military 'blocks'
Climate change • Resource stress • Declining sustainability	Water scarcity Increased push of agriculture into marginal landscapes. Competition between agriculture and urban development for land. Agriculture for chemical and transport feed-stocks rather than food Food scarcity More severe weather events with agricultural land and building infrastructure damage and loss	Large-scale famine Large-scale drought Scarcity of phosphorus and other elements used for fertilisers High energy demand for heating and cooling. Equitable access to food and shelter Financing and rebuilding of flood- and storm-damaged infrastructure

Other global game changers, threats and risks

The global megatrends will determine the strategic positions and actions of most economies but they will also influence industry, law makers and knowledge suppliers in chemistry teaching, research and industry. Each of these groups will need to consider a number of specific global game changers and risks that together with the megatrends are able to cause substantial shocks to all stakeholders.

In 2014[1], the 10 highest global risks over the next 10 years were identified as follows (Table 3):

Table 3: The 10 global risks of highest concern in 2014

No.	Global Risk
1	Fiscal crises in key economies
2	Structurally high unemployment/underemployment
3	Water crises
4	Severe income disparity
5	Failure of climate change mitigation and adaptation
6	Greater incidence of extreme weather events (eg floods, storms, fires)
7	Global government failure
8	Food crises
9	Failure of a major financial mechanism/institution
10	Profound political and social instability

National research priorities

The Australian Government's Science and Research Priorities provide researchers with directions and areas of strategic importance.[2] They help galvanise the research community and identify areas where important breakthroughs, major discoveries and technological advances can be clearly connected to useful economic imperatives. Strategic and applied chemistry allow us to maximise the benefits of existing chemistry knowledge but do not directly stimulate new ideas, advances and understanding.

Scientists can advance our knowledge by filling in 'obvious' gaps in current bodies of knowledge or by extrapolating from what is known, in order to predict where important new developments might be made. This approach is often useful when the target and challenges are evident and clearly demarcated. Chemistry continues to provide important solutions in this way—for example, chemically generated fibres such as rayon and nylon continue to become stronger and lighter, while metal alloys for planes and engines become lighter and yield greater fuel efficiency. Drugs and other pharmaceutical formulations become more efficacious and have fewer side effects.

National priorities help to focus activity in these areas and the Australian Government has outlined nine science and research priorities and several associated practical research challenges for the Australian economy (Table 4).[3]

Given the breadth of these national priorities, it is not surprising that most Australian chemistry researchers actively work in fields that match the priorities. Numerous overseas groups have also tried to set up chemical research strategies and priorities. For example, the call for 'integrated chemical solutions' has been evident for several years in the goals being set by overseas chemistry organisations.

1 Global Risks 2014, WEF 2014 http://www3.weforum.org/docs/WEF_GlobalRisks_Report_2014.pdf

2 http://science.gov.au/scienceGov/ScienceAndResearchPriorities/Pages/default.aspx

3 http://science.gov.au/scienceGov/ScienceAndResearchPriorities/Pages/default.aspx

Table 4: The Australian Government's Science and Research Priorities

Priority	Departments and agencies should give priority to research that will lead to:
Food	**1** knowledge of global and domestic demand, supply chains and the identification of country specific preferences for food Australia can produce. **2** knowledge of the social, economic and other barriers to achieving access to healthy Australian foods. **3** enhanced food production through: • novel technologies, such as sensors, robotics, real-time data systems and traceability, all integrated into the full production chain. • better management and use of waste and water; increased food quality, safety, stability and shelf life. • protection of food sources through enhanced biosecurity. • genetic composition of food sources appropriate for present and emerging Australian conditions.
Soil and water	**1** new and integrated national observing systems, technologies and modelling frameworks across the soil-atmosphere-water-marine systems. **2** better understanding of sustainable limits for productive use of soil, freshwater, river flows and water rights, terrestrial and marine ecosystems. **3** minimising damage to, and developing solutions for restoration and remediation of, soil, fresh and potable water, urban catchments and marine systems.
Transport	**1** low emission fuels and technologies for domestic and global markets. **2** improved logistics, modelling and regulation: urban design, autonomous vehicles, electrified transport, sensor technologies, real time data and spatial analysis. **3** effective pricing, operation, and resource allocation.
Cybersecurity	**1** highly-secure and resilient communications and data acquisition, storage, retention and analysis for government, defence, business, transport systems, emergency and health services. **2** secure, trustworthy and fault-tolerant technologies for software applications, mobile devices, cloud computing and critical infrastructure. **3** new technologies and approaches to support the nation's cybersecurity: discovery and understanding of vulnerabilities, threats and their impacts, enabling improved risk-based decision making, resilience and effective responses to cyber intrusions and attacks. **4** understanding the scale of the cyber security challenge for Australia, including the social factors informing individual, organisational, and national attitudes towards cyber security.
Energy	**1** low emission energy production from fossil fuels and other sources. **2** new clean energy sources and storage technologies that are efficient, cost-effective and reliable. **3** Australian electricity grids that can readily integrate and more efficiently transmit energy from all sources including low- and zero-carbon sources.
Resources	**1** A fundamental understanding of the physical state of the Australian crust, its resource endowment and recovery. **2** Knowledge of environmental issues associated with resource extraction. **3** Lowering the risk to sedimentary basins and marine environments due to resource extraction. **4** Technologies to optimise yield through effective and efficient resource extraction, processing and waste management.
Advanced manufacturing	**1** Knowledge of Australia's comparative advantages, constraints and capacity to meet current and emerging global and domestic demand. **2** Cross-cutting technologies that will de-risk, scale up, and add value to Australian manufactured products. **3** Specialised, high value-add areas such as high-performance materials, composites, alloys and polymers.
Environmental change	**1** improved accuracy and precision in predicting and measuring the impact of environmental changes caused by climate and local factors. **2** resilient urban, rural and regional infrastructure. **3** options for responding and adapting to the impacts of environmental change on biological systems, urban and rural communities and industry.
Health	**1** better models of health care and services that improve outcomes, reduce disparities for disadvantaged and vulnerable groups, increase efficiency and provide greater value for a given expenditure. **2** improved prediction, identification, tracking, prevention and management of emerging local and regional health threats. **3** better health outcomes for Indigenous people, with strategies for both urban and regional communities. **4** effective technologies for individuals to manage their own health care, for example, using mobile apps, remote monitoring and online access to therapies.

Numerous overseas organisations have likewise developed scientific frameworks for improving the focus of research activities. For example:

- in its 2009 roadmap for the chemical sciences, 'Chemistry for tomorrow's world', the Royal Society of Chemistry in the UK listed 10 major challenges, most of which focused on increasing recyclability, sustainability and energy efficiency[4]
- the World Economic Forum (WEF) has over the last few years promoted investment in green technologies and infrastructure in many areas where chemical research can play a major role in improving technologies, rendering them more efficient, or in developing completely new processes.
- several recent publications on green infrastructure implementation[5] and on green infrastructure finance have analysed the green investment landscape.[6]

Opportunities for Australian chemistry research in the 21st century

Chemistry can underpin numerous niche and strategic export industries by careful value-add and by identifying changing market locations and emerging markets.

Table 5: The top ten most important technical challenges for chemistry in the next decade (From Appendix 15. Note: Respondents were asked for the top three most important challenges.)

Alternative, clean, renewable energy	50%
Human health, drug design, delivery, resistance	36%
Food security, agriculture, fertilisers, water	19%
Climate change, CO_2 management	18%
Environment, sustainability, waste management	18%
New materials, polymers, nanomaterials	17%
Alternative and green feed stocks	7%
Improved and green manufacturing processes	5%
Synthesis	2%
Catalysis	2%

* Respondents were asked to provide three technical challenges

Based on the survey results in Table 5, almost all the challenges nominated by researchers focus on complex chemistry issues and the interactions of chemicals in complex environments. The challenge for chemists is perceived to be one of integrating chemistry to help provide long-term solutions—solutions to health, energy and the environment.

While the 19th and 20th centuries focused on single molecules and chemicals that revolutionised the world (see Table 1), the emphasis has shifted somewhat to 'systems chemistry'. The challenges of the 21st century are to find teams of molecules and chemicals that help provide complex solutions, at reasonable cost, with minimal side effects, and which can ultimately be recycled. Systems chemistry represents an enormous value chain. In much the same way that automotive manufacturers are underpinned by a diverse array of component manufacturers, the Australian chemistry industry can increase the value of exports by being part of 'chemical solutions'.

Without chemistry, we could not build wind turbines, fabricate solar panels or create next generation composite materials for buildings, cars, computers, batteries, mobile phones or iPads. Each of these products increases energy efficiency, improves communications or enhances transport capabilities. However, each technology creates a new wave of challenges for recycling and waste management. These are important practical challenges for every country, and the Australian chemistry industry must contribute to global solutions. Smart solutions ensure the longevity of the technology and lead to the creation of new and more secure jobs.

Challenges for the 21st century

As outlined above, 'strategic research' is possible once technological goals and aspirations are clearly identified, for example through focused national priorities. However, the biggest scientific breakthroughs occur through undirected, blue-sky research. These breakthroughs and advances in our understanding of nature and the world around us advance humanity as a whole. By publishing the results from basic chemical research in open literature, scientific researchers can inspire other people such as entrepreneurs, inventors and engineers to come up with ways to apply new knowledge to existing problems. In some cases advances are so profound that entire new technologies result.

Many very fundamental scientific questions need to be answered and in most cases there is no obvious way forward except to carry out systematic experimentation. Scientific discoveries and advances are usually serendipitous and evolve from experimentation in unpredictable ways. This does not imply that chemical experimentation is random—instead it is guided by the results of previous investigation and inspired by the ideas of researchers. Grand scientific challenges exist because of the complexity of the problems we face or because we simply do not understand the core chemical phenomena in sufficient detail. Funding basic chemistry research is the only pathway to breakthroughs in many cases. The following section outlines key areas where Australian chemistry researchers probe the very edge of our understanding or seek fundamental breakthroughs that will later advance the Australian way of life.

4 http://www.rsc.org/images/Roadmapbrief_tcm18-158989.pdf
5 http://news.wef.org/wef-releases-green-infrastructure-implementation-special-publication/
6 http://www3.weforum.org/docs/WEF_ENI_FinancingGreenGrowthResourceConstrainedWorld_Report_2012.pdf

The chemical origins of life

The greatest of all scientific questions is how molecular systems evolved to enable life to emerge on primordial Earth. Chemists in many countries, including Australia, are addressing many questions around this topic such as:

- How do complex organisms arise from simpler chemical structures?
- Is the formation of complex structures and life itself always spontaneous?
- How does photosynthesis—the single most important chemical reaction on earth—work?
- How do chemicals regulate the temperature and climate of our planet?

Answers to these questions may help us find solutions for alternative chemical energy sources to fossil fuels and solutions towards artificial regulation of our climate.

Biological chemistry

Ever since the greatest scientific discovery of the 20th century—the chemistry of DNA—chemists have been making remarkable discoveries about how our bodies work. But there are still many basic discoveries and questions to be answered before we have even a basic understanding of the intricacies of cell metabolism.

- How do proteins fold?
- What is the role of free radicals in the ageing process?
- How does chemistry govern cell differentiation and mitosis?
- How can we do 3D crystallography in real time?
- How can we detect and identify single molecules including toxins, viruses and proteins in complex structures and substrates?
- How can we build a DNA computer? How can we read the base pairs on a single DNA strand?

Publicly funded chemistry research underpins drug discovery and drives Australia's rapidly growing biotechnology and biomedical industries.

These complex questions will undoubtedly improve the health and wellbeing of Australians, but we cannot predict how easily the answers will be found.

Nuclear chemistry

The nucleosynthesis of the elements inside stellar furnaces produces the molecules of the universe. But we know little about other stable building blocks, such as the chemistry of muonium. Other questions include:

- What are the ultimate limits of the periodic table? Is element 137 the uppermost stable element? Current models suggest no element can exist above this atomic number.
- What chemistry can we do with other atomic particles? There are over 100 sub-atomic particles. But all the elements we see are comprised of just three: electrons, protons and neutrons. Is there chemistry beyond these three particles, and what would the applications of this type of chemistry be?

Chemistry of Earth, the environment and beyond

Although we know how molecules behave in the laboratory under standard conditions, their behaviour at high pressure or high up in the atmosphere is less well understood. The transport of chemicals across the globe is a complex process. The chemistry of the entire biosphere must be understood before we can confidently build a sustainable global community. In the shorter term, we must understand:

- the role of urbanisation and resource usage on the emission of contaminants
- the legacy of past mining and disposal activities and the longer-term need for remediation strategies
- the population health effects of emissions and environmental contamination.

Some of the fundamental questions that need to be answered include:

- Using radioisotopes, how can we precisely determine the age of the earth? The solar system? Life on this planet?
- How do raindrops nucleate in the atmosphere? Can we control the weather through chemistry?
- Can we offset greenhouse warming through smart chemistry?
- Do we understand the chemistry of the ozone layer?
- How does chemistry vary on the other planets? Can we mine the outer planets? Can we predict the planets and moons likely to have useful ores?
- Chemistry within Earth's crust occurs under unimaginable conditions at high temperatures and pressures. Can we predict the composition of Earth's mantle and core? Can we predict the existence of important minerals? How does geological chemistry impact us through volcanism and earthquakes?

Discoveries in this field may allow us in the future to manipulate Earth's climate, the chemistry of greenhouse gases in the atmosphere and understand the historic distribution and

What opportunities might planetary exploration present?
CREDIT: INEFEKT69, MILKY WAY PANORAMA WA VIA FLICKR CC BY-NC-ND 2.0

movement of elements during the earth's history. Alternative sources of rare elements from other stellar bodies might be an alternative to invention of new recovery and recycling chemistry methods. Answers to these questions will help us in the long term to understand our changing environment.

Chemistry for energy

Richard Smalley, Nobel Prize co-winner in 2003 for the discovery of C_{60}, nominated energy as the greatest modern challenge for science. There are many potential approaches to finding sustainable energy. Key questions in this area include:

- Can we create room temperature superconductors?
- Can we find replacements for indium (used in computer displays and TVs)?
- Can we lower the cost of ammonia and methanol through the discovery of new catalysts?
- Can we harness solar energy as a means of sustainable energy production (artificial photosynthesis)?
- Can we develop better thermoelectric materials for converting heat into electrical energy?
- Can we build molecular machines?

Discoveries in this area would address many of the challenges in agricultural productivity, energy production and the need for new materials to adapt to the many challenges brought about by climate change and the need for continued technology innovation. Energy research remains essential for Australia, since the cost and availability of energy is central to productivity and economic growth. However, only sustainable or renewable energy that minimises side products such as radioactive waste, greenhouse gases or carcinogenic particulates will provide long-term solutions.

Sustainable chemistry

New opportunities will arise from more sophisticated chemical synthesis that can help with waste minimisation, energy efficiency, zero waste and recyclability. Questions in this domain include:

- Recycling: the new plastic economy—How can we make all plastics biodegradable or recyclable?
- How can we create sustainable battery technology for the 1000 km electric car and for industrial applications?
- Is there a better (cheaper) way to purify water than desalination?
- Can we make fuel cells that operate at 95% efficiency?
- How can we develop new environmentally benign pesticides and herbicides to maintain current rates of crop production?
- How can we manage drug, pesticide and herbicide resistance in a more clever way that predicts and utilises the target organism's response capability.
- How can we make molecular manufacturing feasible? (building structures atom by atom)

Sustainability is tied to chemistry. We can only improve sustainability at all levels from social to geological by understanding the chemical cycles of products and molecules from cradle to grave. These are complex matters and the impact of chemical waste on the Australian environment may well be different to the impact in other parts of the world. It is essential that Australian governments support research into the costs and benefits of products in the Australian context.

Chapter IV
Current state of chemistry in Australia

There are more than 60,000 practising chemists in Australia. This number includes employees in the chemical, plastics, polymers and pharmaceutical industries; academics, students and researchers in the tertiary sector; and chemists working for professional R&D providers such as CSIRO, the state-based environment protection authorities, the Defence Science and Technology (DST) Group and the Australian Nuclear Science and Technology Organisation (ANSTO). It also includes secondary school teachers and key government departments and policy makers.

The stakeholder analysis for this decadal plan included chemists contributing across the value chain:

(1) **Private sector**—companies throughout the chemical industry, biotechnology and pharmaceutical industry: R&D staff, patent attorneys, CEOs and senior executives in companies that are employing chemists or using chemistry-based technologies and methodologies; executives and staff in businesses that provide services to private sector companies that employ chemists.

(2) **General public**—school children and parents, professionals and trades people in various industries.

(3) **Education—primary school, secondary school and TAFE sector**—teachers and students.

(4) **Higher education and academic research sector**—undergraduate students, postgraduate students, research staff, professors and other teaching staff.

(5) **Government research sector and large national research facilities**—employees in research organisations such as CSIRO, DST Group and ANSTO, and staff and senior staff and advisors of various federal and state departments and funding agencies.

(6) **International stakeholders**—advisors, regulators, funding agencies and finance experts.

There are more than 60 000 practising chemists in Australia within industry, research and education. Chemistry is essential to our lives in many, often unseen ways. CREDIT: CSIRO SCIENCE IMAGE

(1) Private sector

Issues and challenges

- The Australian chemistry industry has low innovation efficiency. Mechanisms to stimulate translation and development of new products are needed.
- The chemistry industry needs stronger interactions with the education sector to help ensure students are trained to meet changing industry needs.
- There is a need for government policies that can help drive risk-taking and innovation in the chemistry industry.

(a) Australian chemical industry

The Australian chemical industry is an AU$38.6 billion enterprise employing 60,000 people across Australia and contributing 15% of total Australian manufacturing. The industry directly contributes over $11.3 billion dollars to Australian GDP each year.

This is small by global standards, despite the abundance of natural resources we enjoy. Although Germany has just four times the population of Australia, it is home to at least three of the top ten chemical companies in the world (BASF, Linde and Bayer).[1] The gross revenue of BASF in 2014 exceeded that of the entire Australian chemical industry while the turnover of the company DuPont de Nemours, with US$35.3 billion in sales and 63,000 employees worldwide[2], is similar in size and turnover to the Australian chemical industry.

Large Australian-owned companies include household names such as Dulux, Boral, BlueScope Steel, SPC, BHP Billiton, Rio Tinto and CSR. Yet, only two Australian companies are in the top 110 chemical companies in the world. These are Orica at 69 and Incitec Pivot (Australia) at 103.[3]

Nevertheless, the Australian chemical and plastics industries constitute the second largest manufacturing sector in Australia. Chemicals and plastics are essential in 109 of Australia's 111 industries.[4] The majority of outputs from the chemicals and plastics industry are used as further inputs into manufacturing (valued at $19.3 billion), construction ($6.6 billion), agriculture ($2.9 billion), mining ($1.7 billion) and health care and social assistance ($1.4 billion).[5] Manufacturing is, therefore, the biggest user of inputs from the chemicals and plastics industry, using 39% of chemicals.[6, 7]

(b) The Australian innovation landscape

The overall annual trade balance of Australia's chemical industry has been declining for over a decade.[8] Consequently, the development of new chemical products and business opportunities has also been declining. Market analysts state that '… unless a stronger emphasis is placed on research and development, then Australia will lose any footing in the international market. This is not only due to the number of companies moving processing and research off-shore, but also due to the decreasing number of university students enrolled in chemistry'.[9]

Australia has a considerable number of large, foreign-owned chemical companies. These subsidiaries function primarily as sale points or are involved only in core manufacturing. The industry is heavily weighted towards low-end, primary chemicals that capitalise on the availability of natural resources, such as broad acre agricultural chemicals. These primary chemicals often end up as large volume, low margin feedstocks for the construction, mining and agricultural industries. The final step of developing niche, high-value products has been de-emphasised since the mid-1970s.

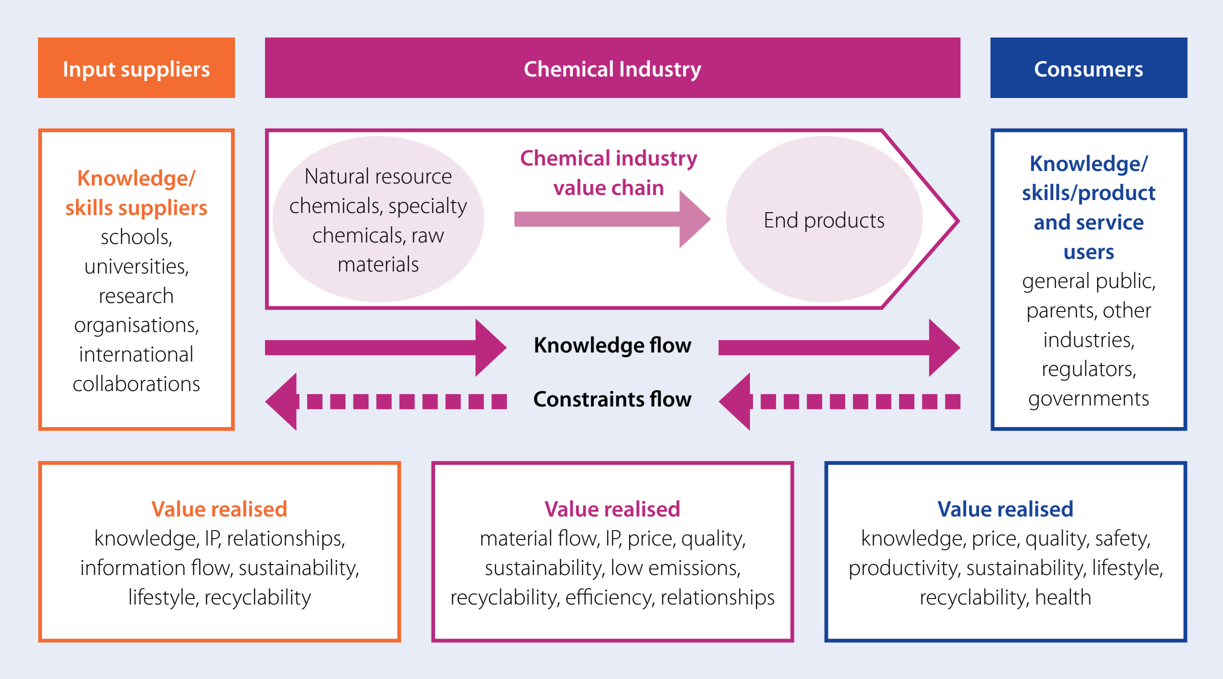
As a result, Australia is poorly represented in the global system for production of the final, advanced manufactured chemicals utilised in advanced technologies, exemplified by the list of key consumer markets. This cannot be attributed to Australia's small population. Of the top 110 chemical companies in the world, at least 10 are from countries with populations smaller than Australia: (Israel Chemicals—Israel; DSM, Shell, Akzo-Nobel, Lyondell-Basell—Netherlands; Syngenta, Clariant, Givaudan, Ineos—Switzerland; Solvay—Belgium).[10] The Scandinavian countries and Switzerland all have highly efficient, technology-based economies with advanced innovation systems and efficient translation mechanisms. They focus on niche applications and ensure they offer unique products that cannot be duplicated easily elsewhere.

The Swiss approach to innovation through support of industry/research sector R&D with a strong focus on SMEs through its Commission for Technology Innovation (CTI) funded schemes is one model that has allowed Switzerland to consistently rank at or near the top of various OECD innovation tables. Swiss chemical companies remain extremely competitive globally, despite the very strong currency. Similar models are also established in Germany.[11]

Australia's poor representation in high-end, speciality chemical development and manufacture is also reflected in its extremely poor OECD ranking for interactions between the research sector and industry, where it ranks bottom of 33 countries. Of the 33 OECD countries assessed, the mean

1 ICIS top 100 Chemical Companies 2014 http://img.en25.com/Web/ICIS/%7B182b8502-fa2d-4cd6-9ad7-133a3db38e16%7D_FC0432_CHEM_201409.pdf
2 http://www.forbes.com/companies/ei-du-pont-de-nemours/
3 http://www.chemweek.com/lab/Billion-Dollar-Club-2012-BASF-takes-top-ranking-for-seventh-straight-year_55646.html
4 The-importance-of-science-to-the-economy.pdf
5 PACIA_strategic_directions_WEB.pdf; see also (PACIA). 'Adding value—a Strategic Roadmap for the chemicals and plastics industry'
6 ABS 2011: Australian National Accounts: Input-Output Tables, 2007–08 Final Catalogue Number 5209.0.55.001. Canberra: Australian Bureau of Statistics
7 http://www.pacia.org.au/aboutus/business_of_chemistry
8 http://www.pacia.org.au/docs_mgr/PACIA_Report1_ElementsInEverything.pdf
9 'Analyzing the Australian Chemical Industry' http://www.researchandmarkets.com/ report April 2014.
10 http://www.chemweek.com/lab/Billion-Dollar-Club-2012-BASF-takes-top-ranking-for-seventh-straight-year_55646.html
11 Steinbeis Stiftung. http://www.steinbeis.de/de/

Figure 2: The chemistry sector adds value to the Australian economy through a flow of products, knowledge and IP



'interaction level' is around 30%. That is, 30% of all firms in these countries collaborate with universities, whereas in Australia it is less than 4%. This is less than in Mexico, Chile and Turkey. The gap is strongest for larger firms, but Australia ranks last in collaboration for both SMEs and large companies.[12]

A key metric for innovation potential is the patenting rate and the ability to translate intellectual property (IP) quickly and efficiently into products, processes and services that the world wants.

Patenting rates in Australia are high. According to the World International Patent Office (WIPO), the chemistry-relevant sections of the following account for nearly 20% of Australian patents: medical technology (7.8%), biotechnology (5.1%) and pharmaceuticals (6.5%). Overall, Australia produces sufficient new IP, ideas and potential innovations to be more competitive. However, translation of IP into products is lacking.

WIPO reports that the Australian entities with the largest number of patent applications in 2013 were CSIRO and Cochlear, followed by Monash University, the University of Queensland and the University of Sydney. Conversely, the top 10 entities submitting patent applications in the US were all industrial companies. Fine organic chemicals (4.1%) also constituted a significant fraction of patents in the US. By comparison, Australia depends far too strongly on public sector research for IP creation and R&D outcomes.

The high focus on public research sector IP, combined with low translation and low R&D efficiencies, together constitute a major weakness which is stifling industry productivity, growth and profitability. As a result:

- there is low awareness of the potential of patentable innovations to drive industry competitiveness in a global, carbon-constrained environment
- Australian chemical companies have a limited understanding of the capacities and capabilities of Australian research providers to help drive innovation
- small industry companies are disadvantaged in their interactions with R&D providers
- the declining viability of Australian chemical companies makes chemistry an unattractive career choice
- traditional university education models limit the value of graduates and research professionals to industry employers

(c) The chemistry 'value chain' in Australia

Chemistry is the largest value-adding chain in Australia and it should not be seen simply as the 'production chain of chemicals'. The true value-adding process is more complex and there are a number of distinct stakeholder communities that contribute to value creation from chemistry, from education and discovery, through to manufacturing and the end users. This is the chemistry 'value chain'.

At each stage of the chemistry value chain, the value increases in different ways (Figure 2). This chain ultimately contributes nearly 6% to the Australian economy each year and is an essential contributor to the high standards of living we currently enjoy. But the sector underperforms compared to similar chemistry enterprises overseas.

For example:

- contributors to the chemistry value chain currently operate in isolation from each other

12 OECD SCIENCE, TECHNOLOGY AND INDUSTRY SCOREBOARD 2013 page 127.

- there is low appreciation of the value of the contributions from other stakeholders and limited recognition of the way performance in one sector impacts performance in another
- government is an essential link in the value chain but appears to be unaware of both its importance through policy setting and its role in ensuring the productivity of each sector and the value chain as a whole
- government is seen as having a focus on short-term cost and red-tape reduction, whereas it needs to take a long-term, proactive and strategic view of the overall operating environment across the entire value chain
- resourcing for translation of research outcomes into products, processes and services is inadequate and of insufficient scale
- stakeholders attribute poor policy development and lack of value chain thinking to the low science literacy of both policymakers and the general public. Policymakers and the public remain deeply suspicious of anything associated with the word 'chemical'.

(2) Public participation and perceptions of chemistry

Challenge

- The chemistry community needs a long-term plan to boost the image of chemistry with the public through better media engagement.

Australia generally has a very low percentage of citizens with a background in science or technology (STEM). This has led to an alarmingly low percentage of politicians with scientific training with the consequence that Australian leaders often fail to grasp the full implications of technical innovation. Conversely, in China, eight out of nine of the top government officials have scientific backgrounds.[13]

Despite the contribution of chemistry to global civilisation, the word 'chemical' continues to conjure up negative views for the general public. There is a need to educate the public away from contradictory statements such as 'chemical-free food' and to recognise the essential contributions chemistry makes. However, such generational change will take at least a decade to implement and will begin with primary and secondary school teachers. In the shorter term, Australian chemists need to make a more concerted attempt to present chemistry in a positive light in the media.

13 President Hu Jintao was trained as a hydraulic engineer and Premier Wen Jiabao as a geomechanical engineer. In Singapore, the president is Tony Tan whose degree is in applied mathematics, while the Prime Minister Lee Hsien Loong also has a degree in mathematics. In Germany, Angela Merkel is well known as a physical chemist, as was Margaret Thatcher in the UK. In many European countries, at least 10% of MPs had a scientific or technical background in the 1980s and that number is rising.

Source: Aberbach, J. D.; Putnam, R. D.; Rockman, B. A., *Bureaucrats and Politicians in Western Democracies*. Harvard University Press: Harvard, MA., 1981.. In the last German parliament, 8 of 26 cabinet ministers were women, while 10 of the inner 16 cabinet had PhDs. Not all of these were chemistry trained, but it is evident that other parliamentary systems do value people with scientific training.

(3) Education

Issues and challenges

- Even at a young age, almost a third of Australian children already have a below-average knowledge of science subjects.
- Fifty seven percent of teachers report feeling unconfident about teaching science.
- By the age of six, many children have already formed a negative opinion about what the word 'chemical' means.
- The quality of the training being offered to secondary school chemistry (science) teachers is lagging dangerously.
- The most critical challenges according to chemistry teachers are:
  - lack of interest of students
  - not enough access to professional development
  - not enough chemistry teachers to talk to
  - poor quality of chemistry facilities
  - class sizes too large.
- The number of students electing to do chemistry (and STEM subjects generally) at school is declining.

International benchmarking of OECD school educational levels are regularly carried out through the TIMSS and PISA rankings. TIMSS focuses on Years 4 and 8 (roughly ages 8 and 12) while PISA assesses students at age 15. TIMSS assesses students across three domains: life sciences, physical sciences and Earth sciences.

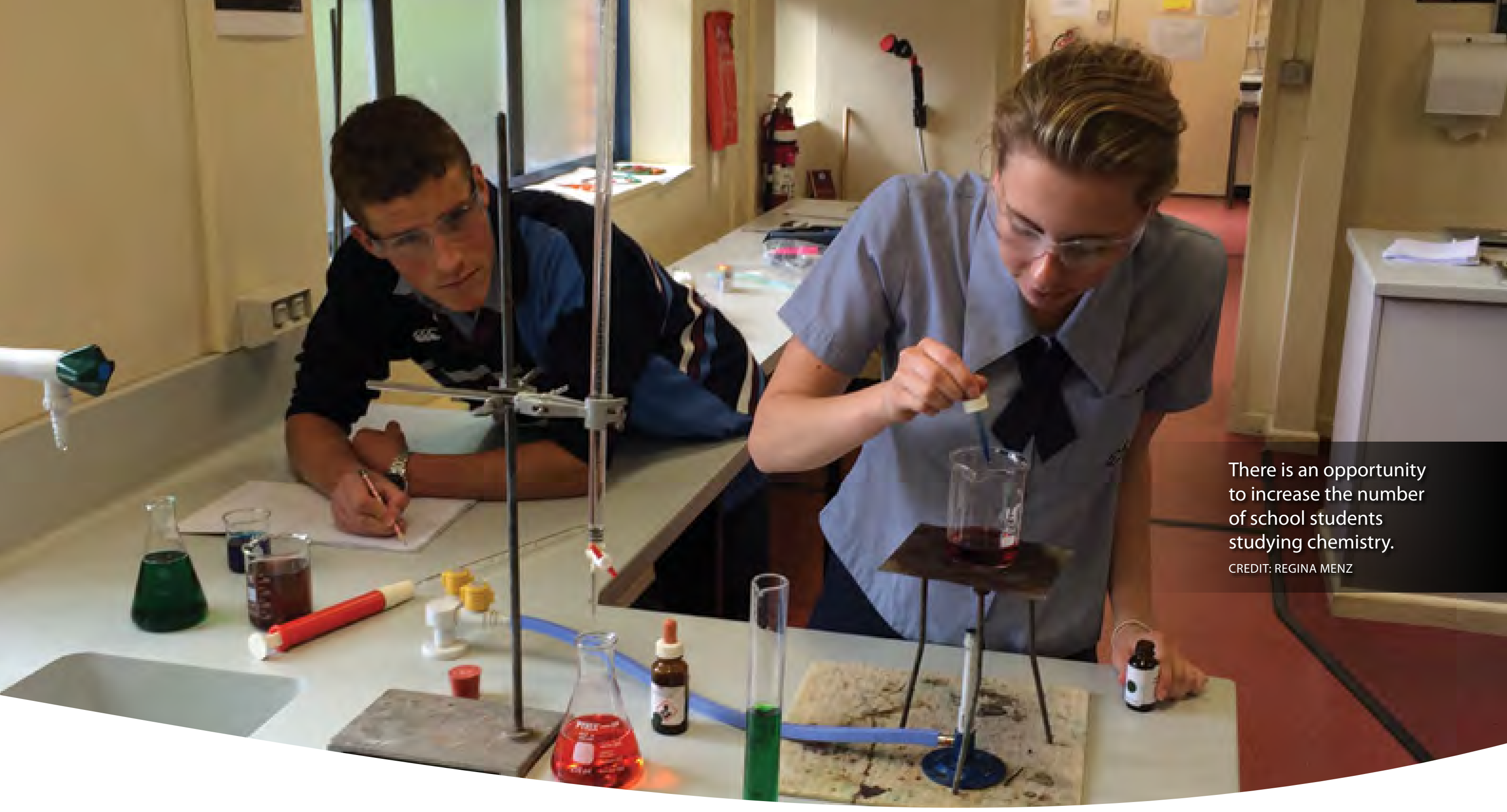
In 2011, the last year for which full data are available, Australia's overall TIMSS score was 516. Although this is above the OECD average, it was significantly below 18 other OECD countries. Of the Year 4 students at age 8 or 9, 29% of Australian students did not reach the international intermediate benchmark.[14] This means that even at a young age, almost a third of Australian children already have a below-average knowledge of science subjects.

According to the TIMSS 2011 data, only 43% of students were being taught science by teachers who were 'very confident teaching science'. Just 51% of Australian students had teachers who classed themselves as 'very well prepared to teach science', and this declined to under 50 % in the areas of physical sciences and Earth sciences.

The TIMSS and PISA results together suggest that to improve chemistry at the school level, the focus needs to be less on technological innovation and more on improving the number and quality of chemistry teachers. It is also important to enable practical study in a classroom environment that is conducive to learning.

Improving staff to student ratios, providing clear-cut career opportunities for staff, and learning chemistry (and science

14 http://www.acer.edu.au/files/TIMSS-PIRLS_Monitoring-Australian-Year-4-Student-Achievement.pdf



There is an opportunity to increase the number of school students studying chemistry.
CREDIT: REGINA MENZ

in general) as early as possible will all lead to significant improvements in STEM outcomes, including chemistry.

(a) Primary and secondary school education

Curiosity about the world around them begins in children at the age of five or six.

The chemistry decadal plan survey interview results were consistent with international survey findings. Primary school children are generally very excited and curious about science and any chemistry experiment at school, but by the age of six, many have already formed a negative opinion about what the word 'chemical' means.

Teachers play by far the biggest role in the development of students' attitudes and learning outcomes in their secondary schooling. Revitalising chemistry teaching is therefore essential to the future of chemistry in Australia. But the quality of the training being offered to secondary school chemistry teachers is lagging dangerously.

There is no uniform curriculum available for primary and lower high school teaching professionals to lift the standards of basic chemistry teaching in schools. (At these levels, students are doing 'general science'). A survey of chemistry teachers (Appendix 14) highlighted which challenges are perceived to be the most severe in the current environment (Table 6).

Table 6: The top five challenges for chemistry teachers

Lack of interest of students	35.9 %
Not enough access to professional development	28.9 %
Not enough chemistry teachers to talk to	24.1 %
Poor quality of chemistry facilities	19.3 %
Class sizes too large	15.7 %

In 2025, the students who will be pondering whether to take Year 12 chemistry are just 6 years old today. This is precisely the age at which many children's curiosity leads them into chemistry and other sciences. Yet our primary school teachers are seldom scientifically trained.[15]

The number of students electing to do STEM subjects at school including chemistry is declining. These subjects are perceived as 'hard', rather than 'challenging'. Furthermore, parents discourage children from pursuing courses which do not appear to have clear vocational directions.

(4) Higher education

Issues and challenges

- Graduates need more transferable skills and more innovation skills.
- As a proportion of all natural and physical sciences, the proportion of those pursuing chemistry has declined.
- Chemistry-dependent industries and employers need good quality graduates, but dwindling staff numbers threaten to reduce the ability of chemistry departments to teach at the levels necessary for industry.
- There are no mandatory minimum entry requirements for chemistry course entrants at universities.
- There is a wide disparity in the quality of chemistry courses.
- There is a lack of a commonly agreed, minimum standard curriculum for a Bachelor of Science.
- Graduates do not always have the skills that industry and government employers need.

15 STEM_AustraliasFuture_Sept2014.pdf

Table 7: Size of full-time employer, Bachelor degree graduates, by field of education, 2013 (%)

Number of employees	2 – 19 Small organisation	20 – 99 Medium organisation	100 or more Large organisation	Total %	Total number
Proportion of BSc chemistry graduates in 2012 (%)	8.2	14.4	77.3	100	97

Australia's 27 tertiary educators in the field of chemistry must be able to specialise in key areas of regional strength, focusing for example on the needs of local industry. They need the capacity to quickly adopt new chemistry associated with important emerging technologies and be able to educate students in these new technologies more efficiently.

In addition to core chemistry expertise, graduates need more transferable skills and more innovation skills. Industries expect higher education institutions to provide them with 'skilled and productive talent' and it is expected that the education sector must create graduates not only conversant with the latest cutting edge research fields but also able to fill the ongoing skills shortages of current commercial organisations.

Despite these concerns, chemistry course numbers increased over the decade to 2010 and consistently represent approximately 12% of the total natural and physical sciences student load in the higher education sector. The overall student load in chemistry increased from around 7,600 to just over 10,000 students, with about half the graduates being women. However, as a proportion of all natural and physical sciences, the proportion of those pursuing chemistry has declined.

The characteristics of the chemical sciences student load have also changed over the decade from 2002 to 2012, with an erosion of the basic bachelor's degree as preferred qualification in favour of postgraduate degrees and other undergraduate, enabling and non-award courses.

Employment prospects for Australian chemistry graduates remain excellent, with 97% of PhDs and 86% of BSc graduates finding employment within 3 months of completing their degrees.

In 2015, it is expected that 80% of science graduates will enter the workforce with a BSc or MSc degree. In other words, only 20% of chemistry graduates will pursue a PhD in chemistry and, of those, only 80% will typically complete.

Of the science graduates in 2012, 69% of BSc chemistry graduates were working in scientific, technical or engineering roles with more than three-quarters of those at an organisation of more than 100 employees[16] (Table 7).

The future of chemistry will be determined by our ability to secure satisfying jobs for the vast majority of chemistry graduates, and the vast majority are not pursuing research but aim to apply their knowledge of chemistry in industry or in other sectors of the economy.

16 Graduate Destination Report 2013. Graduate Careers Australia 2013

The main challenge is to maintain sufficient chemistry expertise in the higher education sector to supply the many chemistry-dependent industries and employers with good quality graduates. Dwindling department staff numbers threaten to reduce the ability of chemistry departments to teach at the levels necessary for industry.

In his analysis, 'Staffing university science in the twenty-first century', Ian Dobson draws the following conclusions on the natural and physical sciences:

> *'Based on full-time & fractional full-time staff, it could not be considered good news to find out that there was a decline in the teaching staff in all of the enabling sciences, despite the increase in the number of students that have to be taught.'*

Dobson then gives an example for the chemical sciences, where the number of experienced teaching staff declined by 4% despite student numbers increasing by 39%.[17]

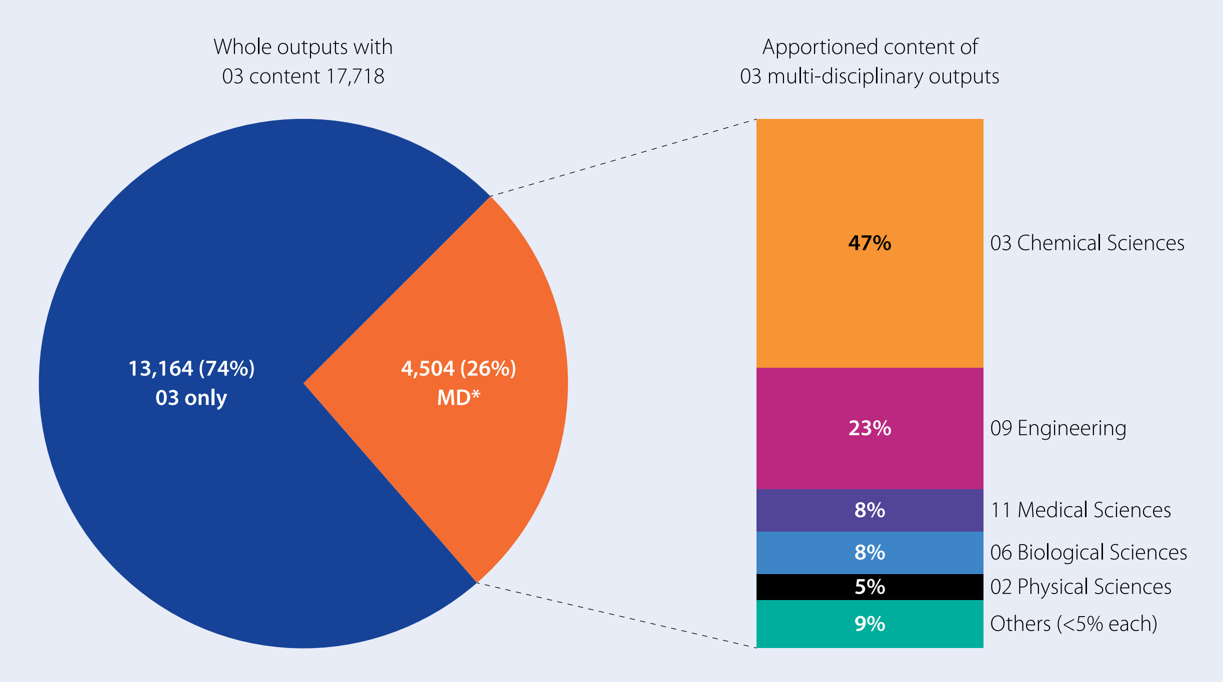
The last decade of university expansion has seen almost 400 FTE more women, and an absolute decline in the number of men (-47 FTE) among teachers in the natural and physical sciences. Much of the expansion in teaching has been taken up by women, but that expansion is due to an increase in the number of limited term positions, and consequently, it is inevitable that the women appointed are more likely to be in limited term positions.

There are no mandatory minimum entry requirements for chemistry course entrants at universities. Each university has its own entry requirements (e.g. cut-off score). Almost all universities offer remedial or catch-up courses for students who were unable to or chose not to do secondary school chemistry. This, in turn, means there is a large knowledge differential across the entry level cohort, ranging from students with no chemistry knowledge to those who have completed an accelerated science course and who have an excellent knowledge of basic chemistry. Yet these students all expect to start and complete a bachelor degree in chemistry in the same timeframe.

There is a wide disparity in the quality of chemistry courses. While in many countries such as Germany, the US, Japan and China, there are numerous high-quality regional universities, in Australia, regional universities have struggled to compete for resources, quality staff and students.

17 Australian Council of Deans of Science 2014: Ian Dobson: Staffing University Science in the twenty-first century http://www.acds.edu.au/wp-content/uploads/sites/6/2015/05/ACDS-Science-Staffing-2014_August_Final.pdf

Figure 3: 03 Chemical Sciences — Multi-disciplinary content profile



There is also a lack of a commonly agreed, minimum standard curriculum for a Bachelor of Science.

Furthermore, due to the large differential in quality of graduates from various universities, there are specific gaps that universities currently do not fill satisfactorily. Thus, graduates do not always have the skills that industry and government employers need.

(a) Academic research

Issues and challenges

- Overall research commercialisation income is just 1.2% of the total research income of the chemistry discipline, indicating low levels of interaction between academic research institutions and industry and low translation efficiency of research outcomes into commercial outcomes.
- There is almost a complete reliance on ARC funding for basic research.
- There is an increasingly poor outlook for long-term careers in academia.

Twenty-seven universities currently offer a BSc (chem.) degree (see Appendix 4) and most of these also support active research programs. The discipline employs almost 1,300 scientists, who are the 'engine room' of the research activity in chemistry in this country. According to the ARC ERA 2015 National Overview,[18] 10 Australian universities were rated at 'above-world-standard or higher', including four Australian universities rated at 'well above world standard' for chemical sciences. The areas where Australian universities fared particularly well include analytical chemistry, inorganic chemistry, macromolecular and materials chemistry, and physical chemistry (including structural). Significantly, there was a 23% growth in publication numbers for the chemical sciences from 2003 to 2013.

Analysis of the ERA 2015 data reveals that: 'Increasingly, government, industry and the research sector are looking towards multi-disciplinary research to solve complex problems. Knowledge flows between usually distinct disciplines attract interest because major advances in innovation often involve collaboration across disciplinary boundaries.'[18] Figure 3 presents an analysis of ERA 2015 outputs for chemical sciences, showing what proportion of outputs are multi-disciplinary.

Although patent activity is high, the overall research commercialisation income is just 1.2% of the total research income of the discipline, with the vast majority coming from competitive government grants. This is again an indication of the very low level of interaction between academic research institutions and industry and of the low translation efficiency of research outcomes into commercial outcomes.

The major funding agency for the academic research sector is the Australian Research Council (ARC), and ARC Discovery grants are the main source of funding for early- and mid-career researchers.

The main concern of the academic sector is the almost complete reliance on ARC funding for research. This lack of diversity is in strong contrast to all other technologically strong economies, which typically have multiple funding sources (although many of these have a focus on strategic and applied research to help the transition to commercialisation).

18 http://www.arc.gov.au/sites/default/files/filedepot/Public/ERA/ERA%20 2015/ERA_2015_National_Report/ERA2015_Section1.pdf

A second concern is the increasingly poor outlook for a long-term career in academia. The challenge is clear from the basic statistics. In other technologically advanced nations, 70% of PhD graduates enter industry while 30% remain in academia. In Australia, the dearth of industry investment in R&D has resulted in 70% of graduates being employed in academia and just 30% in industry.

(5) Government research sector

Issues and challenges

- It is difficult to recruit sufficient numbers of high quality researchers.
- There is poor speed of delivery by the government sector and the excessive red tape associated with working with government agencies.
- There is no clear delineation between the work that goes on in government laboratories and work in universities.
- SMEs are viewed as high-risk customers by the government research sector.
- SMEs consider research provided by government laboratories as unaffordable.

The Australian chemistry research sector is diverse and comprises a wide range of organisations that provide key scientific services and research outputs to government and the community. Significant institutions include CSIRO with its various flagships, DST Group and ANSTO, and researchers in other government departments such as environment protection authorities, the Therapeutic Goods Administration (TGA), Food Standards Australia New Zealand (FSANZ), IP Australia, the Department of Health, the Department of Agriculture and Water Resources, the Bureau of Meteorology (BOM), Safe Work Australia and others. There is also collaboration of the sector with university research laboratories and participation in both centres of excellence and cooperative research centres (CRCs).

It is extremely difficult to obtain figures on the number of chemistry professionals in the government research sector as research personnel are usually employed in an organisational role and not specifically as a 'chemist' or 'chemistry professional'. However, according to our survey approximately three quarters of researchers are male, tenured and under 50 years old and approximately 70% of these are early- to mid-career researchers (Appendix 15).

The fields of work that are covered are broad, with the largest single field being 'organic chemistry', followed by 'macromolecular and materials chemistry'. Typically, these professionals have high qualifications and extensive and varied work experience, with 48% having worked overseas, 45% having worked in industry or business, and 51% having worked in an academic institution.

The most common reason for leaving industry was that government research positions were seen as a better opportunity. The second most common reason was restructuring of the industry or the individual company with concomitant loss of employment. Personal/family reasons ranked third.

A key concern expressed by industry was the poor speed of delivery by the government sector and the excessive red tape associated with working with government agencies.

Members of the academic sector consistently noted that there is no clear delineation between the research that goes on in government laboratories and that in universities. Many academics believed there is a substantial amount of fundamental research funded by CSIRO, for example, that should be carried out in academic institutions. Conversely, some of the smaller universities are doing applied research that could be better carried out by CSIRO.

Another identified issue is that SMEs were viewed as high-risk customers by the government research sector. Compounding this, there was a clear view by SMEs that research provided by government laboratories was unaffordable for them.

(a) Large national research facilities

Issues and challenges

- Maintaining high level national infrastructure such as nuclear reactors, synchrotrons and oceanographic research vessels is difficult? impossible? due to unstable funding mechanisms.
- Attracting world class technical and scientific staff to maintain and upgrade infrastructure is difficult.

Australian chemistry is strongly supported by NCRIS-funded infrastructure, ranging from high-resolution electron microscopes and nanofabrication centres (e.g. Australian National Fabrication Facility, Melbourne Centre for Nanofabrication), through to the Australian Synchrotron and neutron beam facilities at ANSTO.

While chemistry is generally considered 'small-scale' science, chemists are increasingly relying on access to national facilities to answer fundamental questions about material composition or structure. For example, Australian chemists account for 30% of users at ANSTO.

There is strong support for the proposed second Guide Hall for OPAL at ANSTO. Installation of this core infrastructure would open up the possibility of adding a further 15 dedicated scientific instruments/beamlines in future years. Australian chemists also strongly supported the decision to build the Australian Synchrotron.

The Australian Synchrotron supports many activities across the spectrum of chemistry with chemists currently accounting for some 30% of the approximately 5,000 Synchrotron users. Since commencing user operations in 2007, the Australian Synchrotron has hosted more than 27,000 user visits across the 10 operational beamlines. Chemists are major users of the Small X-ray Angle Scattering, X-ray Absorption Spectroscopy, Terra-Hertz/Far-Infrared Spectroscopy, Infrared Microscopy, X-ray Fluorescence

Aerial view of the CSIRO Black Mountain laboratories, Canberra, ACT. Australia's largest scientific organisation CSIRO supports industry and innovation across all aspects of the Australian economy. CREDIT: CSIRO/ROBERT KERTON

Microscopy, Powder Diffraction, and Macromolecular Crystallography beamlines. These beamlines support access to capability that is not feasible in a conventional laboratory setting and consequently enable many high-impact publications and outcomes in areas including:

- development of new battery technologies
- in situ studies of molecular frameworks for hydrogen storage, gas separation and carbon sequestration
- studies of atmospheric photochemistry
- protein purification and structural analysis
- development of new nanomaterials and drug delivery systems
- new polymers, organic semiconductors and photovoltaics
- mineral processing and detection of new ore bodies
- forensic analysis
- environmental monitoring
- the role of metal chemistry and biomolecules in living organisms and cellular biology.

The Synchrotron has been involved in data collection for some 1,000 PhD students in the last five years, with more than 500 honours, masters and PhD theses making use of the facility. The Synchrotron has also been used in more than 2,200 peer-reviewed scientific publications. A number of beamlines are considered world class, with a couple being world leading in their capabilities and scientific productivity. Proposed new beamlines of particular relevance for chemistry include Advanced Diffraction and Scattering, Medium Energy X-ray Absorption Spectroscopy, and Micro-Materials Characterisation. These will provide new, world-class capability in chemistry, materials science, engineering, earth science, agriculture, biomolecular and environmental science, soil science and related applications.

Summary—Connecting industry, academia and research providers

According to the OECD, Australia has the worst performance of any developed country in terms of the connectivity and collaboration between its academic and industry sectors.[19]

Mechanisms for linking industry, the higher education sector and the research sector can be improved and broadened.

The lack of an overarching government policy to facilitate and drive interactions between academia and industry, and the overall perception of research sector inflexibility in dealing with industrial companies and their fixation on existing funding mechanisms, does not make it easy to establish close and lasting industry relationships.

A further problem is the decline in the teaching of technical chemistry. The erosion of the TAFE sector, where most teaching is done on a part-time and contract basis, together with the decline of the technical secondary school system, has led to a drastic decrease in the numbers of skilled technicians who can underpin the chemical manufacturing sector. Revitalising this technical sector can provide a foundation for expansion and also bridge the traditional academic and industry sectors of the chemistry community.

There was consensus that the role of CSIRO as a provider of research to Australian industry (especially SMEs) is not understood by either industry or university-based research providers. A key challenge is the different timelines required. Industry requirements are more at the topical level and require immediate solutions, whereas the research sector is used to solving problems in a five- to ten-year timeframe.

19 http://www.globalinnovationindex.org/userfiles/file/reportpdf/GII-2014-v5.pdf

CREDIT: ISTOCKPHOTO/DAVIDF

Chapter V
The key requirements for the chemistry discipline

Consultation and analysis revealed a number of issues and requirements from key stakeholders. For more details see Appendix 9. The requirements are consistent with a variety of other inquiries into the sector over the last decade.[1,2]

Industry value chain requirements

- All segments of the Australian chemistry community need to develop a unified and collaborative approach for overcoming the causes and impacts of 'chemistry illiteracy' and its poor image with the public. All segments need to take on the responsibility for the way chemistry is portrayed in the media and to work on ways to improve its public image.
- Australia needs more science-literate leaders, policymakers and advisors in government, who can better understand technology-driven change in industry and society.
- The science literacy of the Australian general public needs to be improved, so that Australia can have better informed public debate on global issues which require chemistry for effective solutions.
- Australia needs to be more pro-active in adopting successful models of innovation policies, strategies and schemes from countries that are leading the innovation rankings.
- New chemistry research translation mechanisms need to be developed that are advantageous for all participants. This must be achieved in the current environment of limited industry profitability and limited government support. In particular, mechanisms that facilitate access to translational opportunities for proof-of-concept work are urgently required. However, there remains a strong need for large-scale chemical industry development funds.

1 Australian Research Council. *Mapping the Nature and Extent of Business-University Interaction in Australia*. Canberra: Commonwealth of Australia, 2001.
2 (a) Department of Education, Science; and Training. *Mapping Australian Science & Innovation: Main Report*. Canberra: Commonwealth of Australia, 2003; (b) Department of Education, Science and Training. Measuring the impact of publicly funded research. Canberra: Commonwealth of Australia, 2005.

School education requirements

- There needs to be at least one science-trained teacher in each primary school in Australia.
- The gaps in science literacy of teachers, especially primary school teachers, needs to be addressed as a matter of urgency. It is vital to engage students, to pique their curiosity and to support their interest in science to prevent it from declining prior to entry into secondary school.
- Chemistry education models and engaging teaching materials need to be developed that are easily accessible by teachers in all Australian schools including regional, remote and disadvantaged schools.
- Professional development mechanisms must be developed for easy access by chemistry (science) teachers in regional and remote locations. It is also important to provide secondary school staff with opportunities to undertake upskilling and updating of their knowledge of science.
- Engaging information material needs to be developed for parents and middle school students on the types of employment pathways that a solid chemistry education in secondary school facilitates. This needs to include up-to-date information about developments in the chemistry-related job market.

Higher education requirements

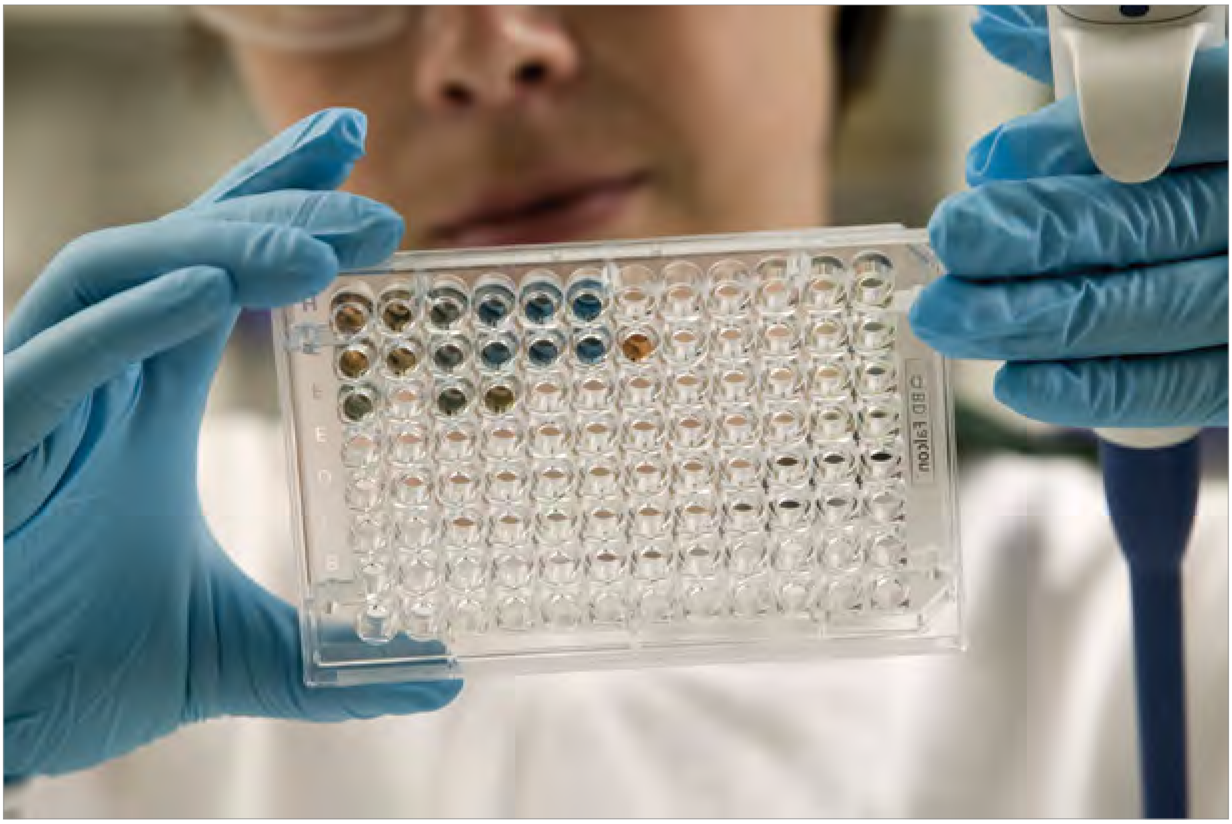
- New higher education models are required for providing chemistry graduates and postgraduates with the skill sets demanded by the industries of the future. This includes more transferable skills such as mathematics and problem solving skills for increased flexibility, as well as more practical industry experience during their studies.
- To be attractive to the more demanding employers of the future, graduates should have cross-disciplinary expertise in a second science discipline such as maths, biology, engineering, toxicology, physics or earth science.
- Higher education providers must develop distinct programs that cater for different career pathways (academic, industry and teaching) to prevent overcrowding of the academic pathway. The current cookie-cutting

pathway is creating cohorts with poor career prospects which do not provide good grounding for either industry or teaching careers. Undergraduates should not be automatically pushed towards an academic career. Instead, specific course curricula must be developed that cater specifically for research, industry and teaching focused graduates respectively.

- Universities need to develop a more flexible approach to teaching chemistry, in order to facilitate faster adaptation to the needs of professional pathways. Courses need to take account of the fact that adoption of new technologies by industry in turn leads to new skill set requirements within the education sector.
- The higher education and school education sectors need to work together to develop new chemistry education models. For example, they need to develop engaging materials that help chemistry teachers deliver improved educational and chemistry literacy benefits to children of all ages and backgrounds (i.e. from pre-school to year 12).
- As parents of school children have little knowledge about the value of a chemistry degree, the higher education sector needs to work together with industry and the secondary school sector to provide suitable information to teachers and parents of middle school children on the diverse job opportunities and career pathways enabled by a chemistry degree.
- The higher education sector also needs to address the issues created by the highly variable chemistry knowledge of students entering tertiary courses in chemistry. In particular, minimum national standards are needed together with clear recognition of the importance of knowledge of other science subjects such as mathematics to the learning of chemistry.

Academic research requirements

- The capabilities of Australian research providers must be strengthened substantially to enable them to become the preferred R&D partners for both Australian and international companies who seek high-end innovation.
- Australian research providers need to actively and routinely provide information about their research capabilities, research equipment and research services to chemical companies and companies in other industry sectors to facilitate appropriate R&D partner selection by industry. This also requires that new metrics for chemistry research efficiency and effectiveness be developed that provide a more balanced picture of each research provider's overall level of competence, rather than just publication-based metrics.
- Research data from Australian research providers (e.g. universities, CSIRO) need to be regularly analysed in a systematic manner to identify potential technologies that could be translated into new products and processes with appropriate support. For example, lists of recent provisional patents lodged could be circulated to industry and universities on a quarterly basis.



New higher education models are required for providing chemistry graduates and postgraduates with the skill sets demanded by the industries of the future. CREDIT: CSIRO/DAVID MCCLENAGHAN

- To improve research efficiency, the Australian research sector has to create mechanisms that enable it to develop longer term research strategies, that are not solely reactive to the government policies of the day.
- Australian research institutions and especially the academic research sector need to abandon their focus on safe, run-of-the-mill, chemistry research projects in favour of high risk, strategic research that can become the source of future innovation. The prerequisite for this is a widening of the range of funding opportunities that are available for different purposes (fundamental, strategic, applied).
- Solutions must be developed for the problem of getting a higher number of start-ups off the ground in the chemistry space.
- More balanced reward and promotion mechanisms in research organisations need to be developed that do not disadvantage commercial activity, industrial collaboration and the time spent on the creation of patentable IP.

Government research requirements

- New and better metrics for chemistry research efficiency and effectiveness need to be developed for the government research sector, that can provide a better view of the research provider's level of excellence in both international and commercial contexts.
- Research sector outputs need to be regularly analysed in a systematic manner to identify potential technologies that could be translated more quickly into new products and processes with appropriate support.
- There needs to be better demarcation of the remit and strategic directions of government research organisations from those of the academic research sector to avoid research duplication and unnecessary competition. This may help better define the 'sense of purpose' that concerns workers in government research organisations.
- There is duplication of services amongst many of the monitoring and registration focused government agencies, which is negatively impacting on both research and commercial productivity.
- The funding mechanisms for research funding to the government and academic research sectors are inefficient in terms of (1) the amount of time and effort required to submit applications, (2) the length of time to assess applications and (3) the quality of feedback to applicants (improved feedback would improve the quality of applications).

Large research infrastructure requirements

- The major requirement for large-scale national facilities is to secure stable, ongoing maintenance of the current, large infrastructure items. Strategic planning is also required to ensure there is a predictable pathway for continuous upgrading of facilities to maintain them at a world-class level.
- There are strong calls to ensure that there is maintenance of skilled technical support in these large research infrastructure facilities to ensure maximum productivity and research efficiency.

Industry requirements

- New, affordable and efficient R&D collaboration mechanisms are required that can foster links between industry and research providers in Australia, in a cash-poor environment.
- The capabilities of Australian research providers need to be strengthened substantially to enable them to become the preferred R&D partners for both Australian and international companies who seek high-end innovation.
- Chemistry research translation mechanisms need to be developed that are viable and advantageous for all participants, in an environment of limited industry profitability and limited government support.
- There need to be better, more flexible models for cost recovery by industry companies and R&D providers, to compensate for the large up-front costs of R&D into new chemical product development. New Zealand has a successful model in place.[3] Other established models exist in Switzerland (Appendix 11).
- New higher education models are required that produce chemistry graduates and postgraduates with the skill sets needed by the industries of the future.
- Government agencies and industry need to develop collaborative rather than adversarial modes of interaction, in order to benefit from and exploit changing regulatory outcomes.
- There needs to be early engagement with industry for chemistry students, in order to build stronger awareness of industry career pathways as an alternative to the traditional academic career model.
- Industry, and in particular SMEs, need to find mechanisms to improve process efficiencies.

Chemistry public image requirements

- The science literacy of the Australian general public needs to be improved, in order to facilitate better public debate on important global issues that require knowledge of chemistry for effective solutions.
- The entire chemistry community needs to work together to change the way chemistry is portrayed in the media and to improve the public perception of chemistry in the public eye.

These requirements are the key inputs to the development of the strategic directions, goals and recommendations made from the decadal plan development process.

3 http://taxpolicy.ird.govt.nz/publications/2015-ris-arrdrm-bill/cashing-out-research-and-development-tax-losses

The decadal plan aims to change the way we see chemistry and to recognise its importance to the Australian way of life. CREDIT: NASA'S MARSHALL SPACE FLIGHT CENTER, SOUTHWESTERN AUSTRALIA VIA FLICKR CC BY-NC 2.0

Chapter VI
The way forward and strategic direction of the Chemistry Decadal Plan

This decadal plan is basing its strategic direction for the next decade on the requirements and needs of the Australian chemistry value chain, discussed in Chapter V. The decadal plan working group established five strategic goals and a number of strategies to achieve these goals during the next decade.

1. Raise chemistry knowledge and skills.
2. Improve the capabilities of the research sector.
3. Raise the level of research and innovation efficiency and improve the translation of research outcomes.
4. Improve the image of chemistry.
5. Implement the decadal plan.

Strategies that support these goals need to be implementable in a national environment, which also takes into account that facts that every sector of the value chain is constrained by its specific funding, operating limitations and business goals.

It will be necessary to balance the short-term current goals (i.e. improving the productivity of the value chain as a whole and all of its sectors) with future long-term strategic goals for becoming competitive and adaptive in a changing operating environment.

This will require cooperation and collective action across the chemistry value chain as well as sustained strategic funding. The five strategic goals are now explored in more detail and some concrete strategies to achieve them proposed.

Strategic goal 1: Raise chemistry knowledge and skills

Strategy 1.1: Improve chemistry education in primary and high schools

- Set a minimum pre-requisite of a Bachelor of Science degree with major in chemistry for secondary school teachers who teach above year 8/9 level chemistry. More highly qualified chemistry teachers will enable better engagement and teaching outcomes for students. If industry placement during the undergraduate degree is one of the features of a chemistry major, then teachers will be able to portray better how chemistry can lead to a valued career for students.
- Set a minimum standard of one science-trained teacher, preferably with a BSc graduate level or at least Year 12 chemistry/science qualification, for every primary school to ensure they can portray science and present chemistry principles and knowledge in an appropriate way.
- Enable all secondary schools to offer modern practical experience in chemistry and develop better models for providing practical chemistry experience to secondary school children in regional and remote areas and in disadvantaged schools, potentially through networked schools or by improving the logistics of access to chemistry teaching infrastructure.
- Promote chemistry teaching careers at all universities—currently the career path of a chemistry or science teacher is not sufficiently promoted at universities. Students are generally directed towards an academic or research career first, an industry career second and only into teaching as a last and less desirable option.
- Improve the image of chemistry teaching as a career—the image of chemistry teaching as a career is currently poor and there is a need for a targeted and sustained activity in promoting chemistry as a whole and chemistry teaching in particular.
- Support ongoing professional development of chemistry teachers and interaction with universities to ensure regular updating of knowledge, teaching techniques and keeping abreast of the field and develop accessible professional development opportunities for remote teachers.

Strategy 1.2: Improve chemistry education in universities

- Mandate the successful pass of an agreed Year 12 national chemistry curriculum and Year 12 mathematics as a minimum entry standard into university undergraduate degrees.
- Agree on a common national school chemistry curriculum that is accepted by all universities.

- Mandate stricter professional accreditation of chemistry degrees in Australia.
- Develop an agreed skills and capabilities profile for chemistry course and training providers and confirm mechanisms for external quality assessment (e.g. government/industry) to ensure course curricula and generic attributes (transferable and practical skills, as well as industry placement opportunities) are met to an acceptable standard.

Strategy 1.3: Improve the chemistry knowledge of policymakers and the general public

- Mandate that every school leaver has an age-appropriate knowledge of chemistry and/or science to ensure that no school leaver will be completely chemistry/science illiterate.
- Develop an agreed outreach program for policymakers that enables the chemistry community to provide information on important chemistry-related issues that will in turn enable informed discussions, decisions and policy development at all levels of government.

Strategic goal 2: Improve the capabilities of the research sector

Strategy 2.1: Address the national challenges of the 21st century relating to chemistry

- Develop a set of research priorities that are tri-annually agreed by all sectors of the value chain. Where possible, these should align with the national Science and Research Priorities of the Australian government.[1]
- Align Australian chemistry more strategically with similar organisations elsewhere, such as the Royal Society of Chemistry (RSC), the American Chemical Society (ACS) and the Chinese Chemical Society (CSC). The establishment of common frameworks and goals can lead to a global voice for chemistry.

Strategy 2.2: Focus on more disruptive chemistry questions and addressing the grand challenges of the chemistry discipline

- Work with funding agencies to ensure that basic, strategic and applied research are all being carried out at the highest level, without conflicting goals and expectations. Support a clearer understanding at all levels between the aspirations of researchers and the expectations of funding agencies.

Strategy 2.3: Maintain and consistently upgrade large research infrastructure to support Australian research at an internationally competitive level

- Consistently maintain and upgrade existing large infrastructure so that it becomes a focus for chemistry-based research in the Asia–Pacific region.
- Improve productivity of large and medium sized research infrastructure.
- Develop a National Chemistry Research Infrastructure Register that includes important medium sized infrastructure, and make it accessible to researchers across the country and industry companies.

Strategy 2.4: Develop more diversified mechanisms for funding and conducting academic research

- Develop a broader variety of funding sources for more directed research in order to address the more practical aspects of solving the grand challenges of chemistry and provide (practical) solutions to the effects of the megatrends, risks and threats. This will need to include novel ways to access funds from parties external to Australia.
- Change the reward and promotion structures in academic research institutions to reward industry engagement, IP creation (patents), and translation. This will require agreed new IP models and translation mechanisms throughout Australia and with all R&D providers, government and the research funding agencies.
- Incentivise stronger R&D investment of industry in academic institution-based R&D to enable increased investment by industry—especially SMEs—in chemistry research.

Strategy 2.5: Streamline and delineate the government research sector from the academic research sector to enable better fit with value chain needs and faster delivery of impact

- Clearly define and delineate between core strategic research in the national interest that should be taxpayer funded, and R&D that is for commercial benefit and should be funded by industry. This delineation should be as clear as possible and supported by appropriate funding arrangements. Fundamental research should focus on areas where scale and teams are needed, which is where universities generally do poorly.
- Develop mechanisms that can provide better R&D services to international organisations, large national companies and SMEs. These mechanisms should take into consideration current funding constraints of both providers and industry segments.
- Develop models to enable SMEs to develop into more advanced chemical companies that deliver higher value through innovative products.

1 The Department of Industry, Innovation and Science released the complete list of National Science and Research Priorities in May 2015 (see www.science.gov.au).

Strategic goal 3: Raise the level of research and innovation efficiency and improve the translation of research outcomes

Strategy 3.1: Improve innovation capability of the academic research sector to enable faster and more targeted delivery of research outcomes

- Develop and incentivise better mechanisms for research translation that benefits all parties at the outset. These new mechanisms need to overcome current drawbacks for both industry (lack of speed and high cost) and the academic sector (limitations on ability to publish, directed research, project management based research process). Better mechanisms are needed to increase the speed with which research outcomes are attained in order to improve research productivity. Project management systems for research translation need to be developed.
- Improve the delivery times of R&D outputs to industry by becoming faster in delivery and improving interactions with customers and other parts of the chemistry value chain).

Strategy 3.2: Develop mechanisms and processes for lifting the innovation capability, productivity, competitiveness and adaptability of the Australian chemical industry

- Develop a pilot scheme such as similar to the Swiss CTI model with innovation mentors who specialise in supporting both chemical industry technology development and start-up companies. This model would enable the matching of industry company needs with research provider capabilities to address specific needs and deliver high tech or high end competitive results.
- Develop processes and mechanisms for building more formal and long-lasting relationships between industry, the higher education sector and research providers. This should focus on demonstrating and realising value for industry and research providers. The process should be largely driven by independent industry participants to ensure focus is on new products or processes and on productivity, effectiveness and results.

Strategy 3.3: Improve the effectiveness and efficiency of interaction and communication throughout the chemistry value chain

- Improve the interactions and communication between all sectors of the chemistry value chain. Currently each sector has its own affiliation banner to which it belongs, such as PACIA for industry, RACI for chemistry researchers, ATSE and others. A more integrative approach is needed to facilitate communication, interaction and a common response of the chemistry value chain to issues and threats.
- Develop and agree on a common communication plan for the complete value chain. Currently each sector has its own plan, developed with very little consultation between sectors, and this needs to be improved for delivering long-term benefits. The goal is to limit confusion within and outside the value chain and to enable a unified response to issues and problems.

Strategic goal 4: Improve the image of chemistry

Strategy 4.1: Promote chemistry to the general public and emphasise its value to society

- Develop and fund an agreed media strategy to enable a constant media presence in the major media to provide frequent information about positive chemistry results and the value of chemistry in general. Implement a structured approach to increase the positive reporting and exposure of chemistry on multiple media platforms to match other science disciplines such as, astronomy, space science, biology, medicine and biotechnology.
- Work with universities, research institutions and industry to develop and implement an agreed and nationally coordinated outreach program and ensure that every school in Australia has physical contact at least once a year with a chemistry scientist, senior chemistry university student or industrial chemical professional.
- Develop better mechanisms to enable individuals of the general public to access chemistry professionals. This could be in form of a 'find a chemistry expert' scheme that ensures that anyone can find access to a chemical expert to get answers to chemistry-related questions. The chemistry community needs to have a pool of experts available for media comment on chemistry-related stories in the media.

Strategic goal 5: Implement the decadal plan

Strategy 5.1: Form and fund a decadal plan implementation committee that represents and focuses on the interests of all segments of the chemistry value chain

- Appoint a committee with members from all sectors of the value chain and develop appropriate terms of reference.
- Source funding for the operations of the committee.
- Develop a budget for implementing the plan.
- Develop reporting mechanisms, KPIs and milestones for the committee, including a mid-term review of the plan.

Strategy 5.2: Develop a value chain roadmap and a long-term rolling strategic research and development plan for adaptation to global, regional and national challenges and opportunities

This is expected to be part of the remit of the decadal plan implementation committee.

Sustainable agricultural practices, better soil chemistry and efficient irrigation are vital to the expansion of Australia's food industries.
CREDIT: ISTOCKPHOTO/TRAPPY76

Chapter VII
Implementation

The way forward

At a glance:

- The strategies outlined in this decadal plan are intended to achieve greater cohesion and connectivity across the chemistry sector, and to support each segment of Australia's largest industrial value chain.
- An implementation plan will be developed by a committee drawn from stakeholders across the chemistry community; however the working group believes that implementation should be an industry-led initiative.
- The work of the committee must be actively supported by the wider chemistry community in order to have the appropriate authority to develop and oversee the implementation of the strategies in the decadal plan;
- A mid-term review of the decadal plan in 2020 will assess progress, analyse outcomes and determine necessary changes.

The next steps

In 2016, chemistry stakeholders will come together to form a group of high-level representatives to translate the decadal plan into action. This implementation committee will be drawn from representatives of industry, education and academia and will develop an implementation plan that will identify specific initiatives and opportunities to progress towards the chemistry community's strategic goals (Figure 4).

The success of the implementation committee depends on active support from the chemistry community. In particular, the chemistry community needs to:

- directly support the work of the committee by
  - providing high-quality, constructive input to the committee's work
  - providing time, expertise and resources to the work of the committee where appropriate and available
  - actively identifying opportunities for the implementation of the decadal plan in individual networks and workplaces.
- build a critical mass for the decadal and implementation plans by
  - creating awareness about the work of the committee and the progress of the plans with our colleagues, managers, stakeholders and professional associates
  - engaging with our peers with our ideas for the plans
  - strengthening the voice of chemistry by taking part in sector-wide initiatives to engage with business, government and the wider community.
- create a cohesive, committed and respected chemistry community by
  - committing to forging chemistry relationships outside of routine activities
  - committing to connecting students and junior colleagues with the Chemistry community, through industry bodies and professional associations

Figure 4: The next steps

START	Within two months	Within six months	Within 12 months	Within 18 months
Constitution finalised	Enabling framework finalised (terms of reference, meeting schedule, secretariat support arrangements, final composition)	Implementation plan finalised	Draft set of specific initiatives to operationalise the implementation plan	Proposed initiatives connected with the necessary leadership, stakeholders and resources to enable their implementation

Australia is home to the world's most beautiful coastlines, beaches and coral reefs. We must ensure we understand how human habitation affects our unique environment.
CREDIT: DR ADRIANA VERGÉS, PHOTO BY JAMES SHERWOOD

- committing to promoting a culture of collaboration throughout the sector.
- assess, evaluate and improve the plan by
  - initiating and contributing to a mid-term review of the progress and strategies of the decadal plan and the implementation plan in 2020.

By working together as a united community, the sector has the opportunity to realise the vision and the objectives set out in the Chemistry Decadal Plan. If the implementation committee has the community behind it, its ability to influence business, government and stakeholders will be greatly magnified.

In Appendix 10, we present initial scoping of the implementation pathway. This describes initial findings concerning the results of the Dependency Structure Matrix Analysis on the likely interdependencies, which will need to be taken into account when creating timelines and a sequence for implementation.

Australia must continue to invest in maintaining the vitality and strength of its chemistry sector. The Chemistry Decadal Plan provides the tools to make this possible.

Appendices

Appendix 1
National Committee for Chemistry

The Decadal Plan Working Group was overseen by the National Committee for Chemistry whose members in 2014–15 were:

Professor Paul Bernhardt
(2015–2016 President of the RACI, University of Queensland)

Professor Evan Bieske
(University of Melbourne)

Professor David Black
(UNSW Australia)

Professor Mark Buntine
(2013–2014 President of the RACI, Curtin University)

Professor Michelle Coote
(Australian National University)

Dr Oliver Jones
(RMIT University)

Dr John Lambert
(Biota P/L)

Ms Regina Menz
(Education Officer, Catholic Schools Office Armidale)

Professor Paul Mulvaney
(Working group Chair, University of Melbourne)

Professor Rich Payne
(University of Sydney)

Dr Greg Simpson
(CSIRO)

Professor Martina Stenzel
(UNSW Australia)

Dr Dave Winkler
(CSIRO)

Appendix 2
Chemistry Decadal Plan Terms of Reference

Inception

The proposal to undertake construction of a Chemistry Decadal Plan was an initiative of the Australian Academy of Science in 2013. The proposal was embedded into the terms of reference for the Academy's National Committee for Chemistry (NCC) in mid-2013.

The chair of the NCC then consulted with Heads of Chemistry at their annual meeting at ANU in October 2013. Their strong commitment to the process led to donations and funding of around $60,000 to begin the decadal plan development process.[1]

In December 2013, a joint submission from the National Committees for Chemistry, Agricultural Science and Earth Sciences through the Learned Academies Special Programs (LASP) of the ARC secured further funding to enable the decadal plan to be undertaken. The Decadal Plan Working Group thanks the ARC for its commitment and support. The NCC formally agreed to undertake the process with funding in place at its meeting in December 2013.

1 Donations are listed in Appendix 8. Without this matching commitment it is unlikely the process could have been undertaken.

Decadal Plan Terms of Reference

The terms of reference for the Decadal Working Group were to:

- consult with all sectors of the chemistry value chain, including the primary and secondary school sectors, higher education sector, the research provider sector, industry regulators, industry and government policy makers.
- provide strategic science policy advice to the Academy for input into science policy statements, and (with the approval of the Executive Committee of Council) to the Australian Government and other Australian organisations.
- connect the Academy to chemical science and scientists in Australia.
- ensure Australia has a voice and a role in the global development of chemistry.
- facilitate Academy links to all sectors of the chemistry value chain, in order to raise the relevance and viability of chemical science and to promote development of the discipline.
- facilitate the alignment of Australian chemical science to the global chemical science community and global scientific goals.
- produce a decadal plan for chemistry in Australia.
- produce an implementation plan upon acceptance of the strategic direction of the decadal plan.

Appendix 3
Decadal Plan Working Group

A potential list of working group members was drawn up in January 2014 and the final composition of the group was finalised in March 2014. The working group was drawn from major stakeholders across Australia, including different subsets and specialisations within the field and representation from industry through PACIA and CSIRO as well as secondary school teaching representatives.

The final Decadal Plan Working Group which prepared the plan comprised:

Professor Paul Mulvaney
(Chair) (University of Melbourne)

Professor Paul Bernhardt
(University of Queensland)

Professor Mark Buntine
(Curtin University)

Mr Peter Bury
(PACIA)

Professor Emily Hilder
(University of Tasmania)

Ms Samires Hook and **Dr Poulomi Agrawal**
(Australian Academy of Science)

Professor Dianne Jolley
(University of Wollongong)

Professor Kate Jolliffe
(University of Sydney)

Dr John Lambert
(Biota P/L)

Professor Steven Langford
(Monash University)

Ms Regina Menz
(Education Officer, Catholic Schools Office Armidale)

Ms Samantha Read
(PACIA)

Dr Elke Scheurmann
(Rapid Invention P/L)

Professor Joe Shapter
(Flinders University)

Dr Greg Simpson
(CSIRO)

Ms Alexandra Strich
(University of Melbourne)

Professor Brian Yates
(ARC and University of Tasmania)

For hosting decadal plan town hall meetings at their campuses, we also thank:

Professor Peter Junk
(James Cook University)

Professor Barbara Messerle
(UNSW Australia)

Dr Robert Robinson
(ANSTO)

Appendix 4
Australian universities offering bachelors degrees in chemistry

The following 27 Australian universities offered RACI-accredited bachelors degrees in chemistry in 2015

Macquarie University

University of New England

University of Melbourne

Charles Sturt—BSc (analytical)

University of Newcastle

University of Sydney

UNSW Australia

University of Technology Sydney

Western Sydney University

University of Wollongong

Flinders University

University of Tasmania

Griffith University

James Cook University

Queensland University of Technology (BAppSc)

University of Queensland

University of Adelaide

Deakin University—BForensicScience (hon.)

LaTrobe University

Monash University

RMIT University—BSc (Applied Chemistry)

Swinburne University

Victoria University

Curtin University

Edith Cowan University—BSc (Applied and Analytical Chemistry)

Murdoch University

University of Western Australia

Appendix 5
Decadal plan process

Overall process

The Chemistry Decadal Plan is a document that is defining strategies for guiding future policy and investment in chemistry research and development and it also aims to achieve a general improvement in chemistry capabilities across the chemistry value chain. To enable this to occur, the Decadal Plan Working Group employed a general business planning approach to its stakeholder consultation, analysis and strategic planning (Figure A1).

The first step in this approach is to establish the current state of the field in Australia and overseas and to carry out a type of SWOT analysis. The current business strategic position was

Figure A1: Decadal plan business planning approach, adapted from Graham Hubbard (2000) Strategic Management

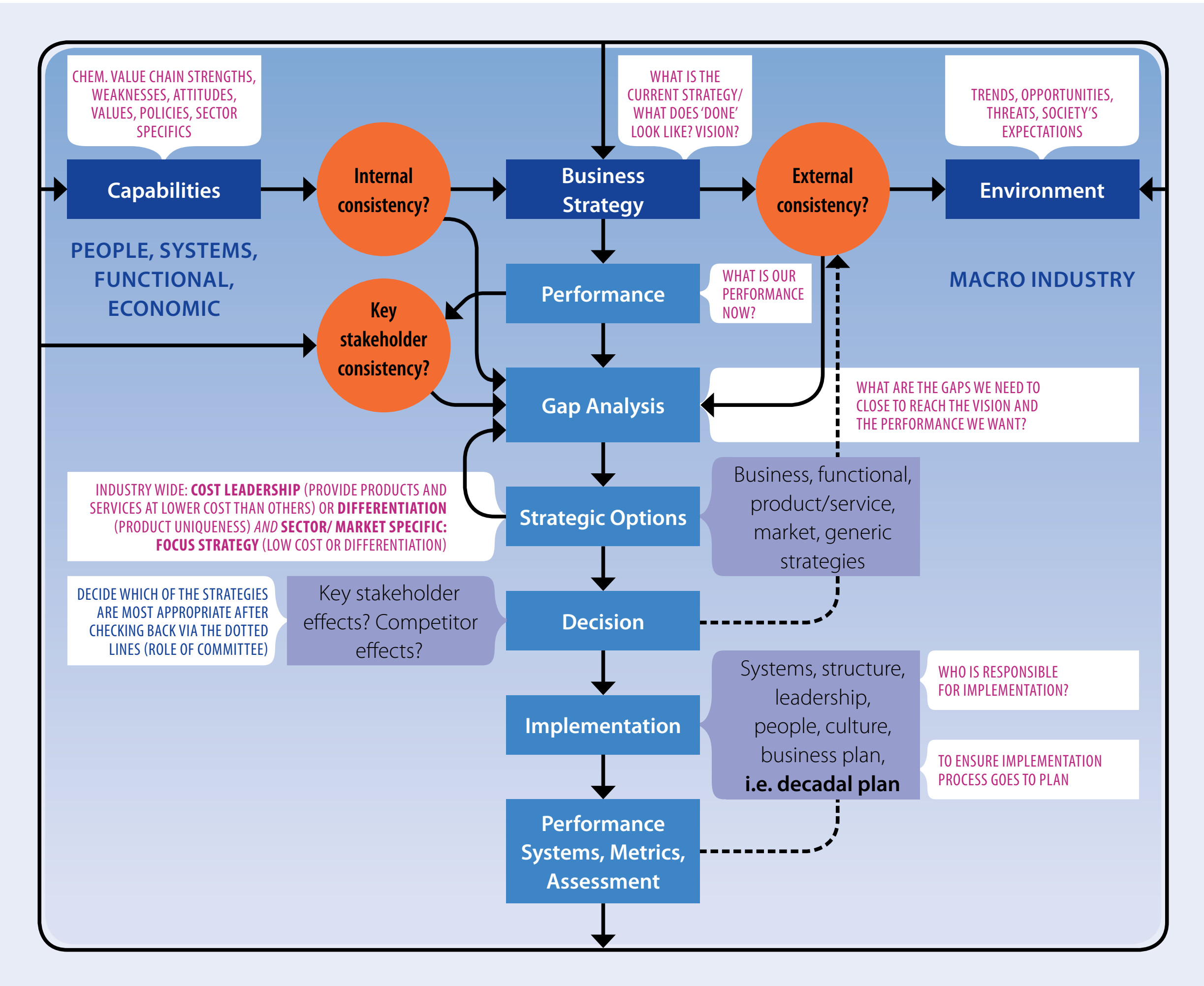
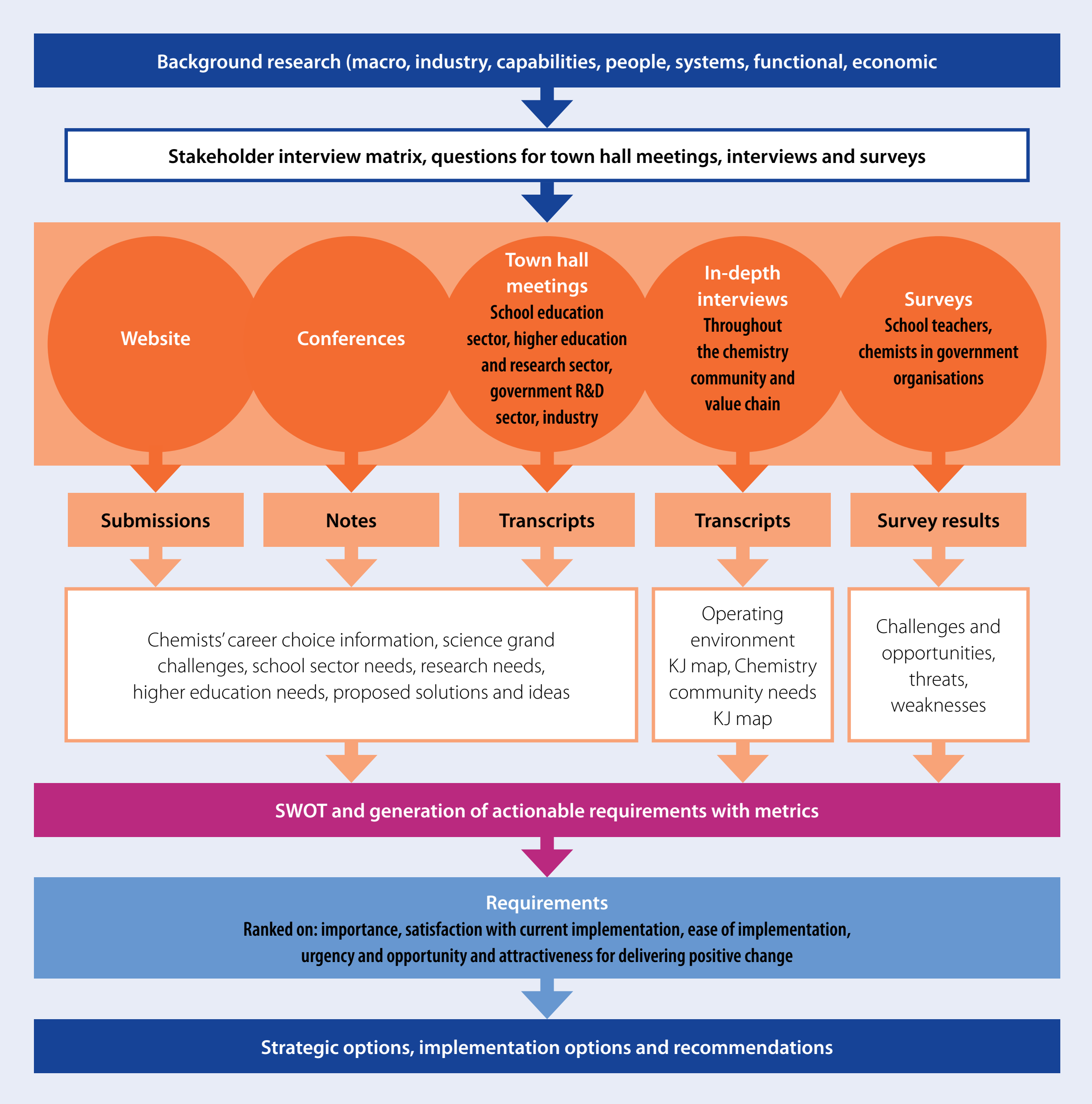


Figure A2: Decadal plan process translated into action steps



defined by using the outcomes of the 1993 chemistry review,[2] together with current government science and funding policies, and combining these with the current (PACIA) and research organisation strategic plans. The process steps needed to develop this strategic plan were then translated into a number of action steps as outlined in Figure A2.

Background research

After analysis of the strategic position of the chemistry value chain and determining which recommendations of the existing strategic plans have been adopted and implemented since 1993, an extensive background environment analysis was carried out about the chemistry value chain in the national and international context. (Appendix 13).

This capability analysis of the chemistry value chain, which consisted of further background research and intensive stakeholder consultation, provided the key information about the current performance and issues and requirements of the chemistry value chain. The process consisted of six strands for which different methods and approaches were used:

- 26 public meetings held across Australia covering universities, research providers and industry forums. The number of attendees at these meetings exceeded 700 people. A summary of these meetings is reported in Appendix 7.

2 Spurling, T. H.; Black, D. S.; Larkins, F. L.; Robinson, T. R. T.; Savage, G. P., Chemistry—A Vision for Australia. In Australian Government Publishing Service, 1993; pp 1–79.

- In-depth interviews with 62 members of the chemistry community, ranging from school children to CEOs and government officials. This process covered all sectors of the chemistry value chain. (See Appendix 6 for a list of interviewees and people consulted.)
- On-line surveys of staff at major chemistry-based organisations such as state-based environment protection authorities and CSIRO, and of science/chemistry teachers across Australia. The analyses of these surveys is incorporated into the main decadal plan document.
- Attendance and discussions of the Decadal Plan Working Group members at a number of chemistry and science teacher conferences and forums.
- Email submissions to the working group. These were used for input into the overall capability and performance analysis.
- Website submissions via a dedicated site (www.chemistrydecadalplan.org.au). These submissions were analysed and used as inputs into strategy development.

Town hall meeting process

The town hall meetings were widely advertised within the relevant research organisation and their local departments/divisions/campuses or by the conference organisers of conference-based meetings.

In general, these meetings were organised and promoted either by the relevant head of the organisation, the head of the chemistry department, the Dean of Science, a member of the National Committee for Chemistry or a member of the Chemistry Decadal Plan Working Group. The industry meeting in Melbourne was organised and promoted by the BioMelbourne Network.

Each of the town hall meetings was introduced by the town hall meeting organiser or a working group member. A short presentation gave an outline of the decadal plan process, followed by a set of five to eight slides with questions to guide the discussion.

Each of the meetings were recorded, using either the organisation's recording technology or digital pocket recorders.

The recordings were analysed to identify common issues throughout the chemistry value chain and issues that were specific to individual stakeholder segments. The focus of the analysis was the identification of new issues that were not identified using the other research methods such as stakeholder interviews and surveys.

In-depth interview process

The interview process followed an established process used in new product and service development to identify customer issues and requirements in the context of developing new strategies for meeting customer needs, while becoming more competitive in the market.[3]

Stakeholder matrix

To ensure that the breadth and depth of the chemistry stakeholder community was covered adequately, an interview matrix was constructed that contained all its major segments, as identified in the background research. Within each segment a number of individuals were selected who had sufficient expertise within their own sector, and in many cases in adjacent sectors, to comment and provide input via the interview process. A list of approximately 200 individuals was used to establish contacts and set up a balanced interview matrix. Ultimately 40 in-depth, 25–90 minute long interviews were held, either by visiting the interviewees in their place of work or by phone.

Interview guides

For each interview a set of five questions with additional prompts was used to ensure that a common and structured framework was followed throughout the interview. The interviews were recorded and transcribed. It was made clear to the interviewees that their interview recordings and transcripts were to be kept confidential to ensure frank conversation. An example of an interview guide with its questions and prompts is included as Attachment 1 at the end of the Appendix 13.

Extraction of issues and needs

The transcripts were then used to extract statements relating to issues and problems in the current operating environment of the interviewees and to identify their needs and requirements for future improvements.

The interviews were recorded and transcribed and the transcripts were then used to draw out common issues and requirements. The methodology used for the evaluation of the interview information was based on that described by Burchill and Hepner Brodie in their 1997 book 'Voices into Choices'[4] and Karl Ulrich of the Wharton School at the University of Pennsylvania in 2003.[5] This method uses KJ diagrams[6] that focus on language data rather than numerical data. The method is named after Professor Jiro Kawakita from the University of Kyoto. It is especially useful for problem and needs identification and for developing requirements for solutions to problems. Consequently this method has been

3 Ulrich, Karl and Steven D Eppinger: Product design and development, 2011
4 Burchill, Gary and Christina Hepner Brodie.: Voices into Choices. Joiner 1997
5 http://opim.wharton.upenn.edu/~ulrich/documents/ulrich-KJdiagrams.pdf 2003
6 A good description of the method and its differentiation from affinity diagram methods is given here: http://www.isixsigma.com/tools-templates/affinity-diagram-kj-analysis/effective-use-special-purpose-kj-language-processing/

widely used in new product and service development. One of the distinct advantages of this method is that it can identify issues and relevant requirements quickly, even with a small set of interviews.

From the interview information, approximately 600 interview statements were selected that vividly described the working environment and related issues while a further c. 950 statements were collected relating to the clearly stated needs of interviewees in their operating environment. These statements were then analysed in two, one-day workshops, where the large numbers of statements were reduced to two KJ maps (see Appendix 13) with around 45 statements each that were representative of all the statements made. The two KJ maps were:

1. **The current operating 'environment map'** showing positive strengths of the current operating environment in the chemistry community and outlines current issues that lead to sub-optimal functioning of the relationships within and between segments of the 'chemistry community'. This map answers the question 'How effective is the chemistry community in contributing to the overall performance and competitiveness of the sector in Australia?'
2. **A chemistry community 'needs map'** showing what the expressed needs of the different segments of the chemistry value chain are.

These needs are then used to identify and construct strategies for long-term viability and competitiveness of the stakeholder segment and the complete stakeholder community in the global context.

Requirements generation

The interviewees were selected on the basis of an assumed deep knowledge and experience in their segment of the chemistry community. The issues, problems and shortcomings described by interviewees were translated into an actionable requirement that could then guide the development of implementable solutions. To develop actionable requirements for implementable solutions the following process was used. An example of how this approach is actually implemented is shown in Figure A3.

Taking one operating environment statement and one needs statement (in no particular order or preference) the key issue that ties these two statements together is defined.

To address this key issue, which is usually having a negative impact on what the chemistry community wants to achieve in the long term, a number of requirements were then developed.

Going through a list of 50 to 60 operating issue statements and the same number of needs statements from the two maps, approximately 80 to 100 requirements were defined. These were then grouped into logical groups of similar requirements, which were then rephrased into a group of 39 specific requirements.

Figure A3: Generation of requirements

Interviewee needs statement
Australia needs to adopt world's best practice in industry processes and policy making.
Interviewee operating environment issue statement
Negative community and parent attitudes to science and education limit children's future prospects.
Key item
Scientific illiteracy has a broad negative impact on several sectors in Australia. There is unawareness of the impact of science illiteracy on policy making, strategic planning and process implementation in industry.
Actionable requirements
All children must have a specific minimum knowledge of chemistry when they leave school. All children must at least meet the minimum international competence benchmark in STEM subjects (including chemistry) in all assessment years. The science literacy of politicians at all levels must be increased. Chemistry literacy of decision makers in private sector companies must be increased for better strategic planning decisions on infrastructure and process upgrades.
Requirements and metrics
Numbers of school students meeting international benchmarks; numbers of politicians in parliaments and company executives in decision making roles with science degrees. Numbers are increasing over a specific timeframe (decade).

This process of translating the 'needs' stated in interviews in the context of the issues is necessary because not every 'need' that an interviewee voices is automatically a requirement. For example, if an interviewee states that 'the government should keep tariffs up so that imported chemical products are more expensive than locally produced ones' and a context issue statement says 'The awareness of Australian companies about the need for innovation is low' does not mean the requirement statement should be taken at face value, which would then read that 'import tariffs should be maintained to allow the low awareness status to persist'. The key issue in this context is competitiveness or the lack of competitiveness due to barriers relating to innovation. Requirements in this example need to address this key issue and how to survive without tariffs.

Requirements ranking survey

The list of 39 requirements was then converted into a survey format using a SurveyMonkey web-based survey format and sent to the interviewees and a wider cross section of the chemistry stakeholder community. A stakeholder email list, segmented and balanced according to the original interview matrix segment proportions, was used to distribute the SurveyMonkey survey.

Each respondent was asked to rank each of the requirements on:

1. **Importance** for them in their operating environment—from Zero (no importance at all) to 5 (extremely important).
2. **Satisfaction** with how well the requirement is currently met—from Zero (not met at all) to 5 (completely met already).

From the email list of 300, 59 full responses were received. For each requirement a mean ranking score was calculated for both importance and for current satisfaction on how well it was met.

Based on the mean importance and satisfaction scores an 'opportunity' score was then calculated for each requirement. This allowed us to identify those requirements that had high importance scores as well as low satisfaction scores, and to rank the requirements according to their 'opportunity scores'.

Requirements categories

Requirements that are used for developing solutions to important issues can be allocated to one of four categories, based on Kano[7]:

1. **Requirements for solutions that must be met**, also called 'must-haves' or 'threshold' requirements. They are specific requirements that will result in considerable dissatisfaction if they are not met. They are high on the importance ranking scale and low on the satisfaction ranking scale. Often they are not even mentioned because stakeholders assume they are already met in current solutions—because the provider of the solution should know how important these requirements are. Examples for must-haves are functioning brakes in a car, where buyers at purchase of the car don't even ask whether the car has any brakes, they are assumed to be there and fully functioning. However, if the brakes are not functioning properly, satisfaction is very low. These requirements are those in the bottom right quadrant of Figure A4, located below the line labelled 1.
2. **One-dimensional requirements**, where satisfaction rises proportionally to the importance of the requirement. The more mileage a car drives with a given amount of fuel the better, or the less fuel per 100 km the better. Competitive advantage results from delivering either higher quality, more features, lower cost, more speed and so on for the same or similar inputs than competitors. Dissatisfaction arises from not meeting minimum standards. These requirements are usually fully understood by stakeholders and can be voiced by them in terms of metrics. These requirements usually cluster along the diagonal line labelled 2 in the upper right quadrant of Figure A4.
3. **Delighter requirements**, that would provide a point of positive differentiation compared to competitors. Often these are requirements that stakeholders have not thought about before they are translated into desirable solutions. Initially they are not seen as of high importance (e.g. air bags in cars). The first driver airbag was a 'delighter'. Eventually all delighters become linear, one-dimensional requirements (the more airbags the better) and later to must-haves (new cars without airbags don't find buyers). These requirements are located in the top left quadrant in Figure A4 and above the line labelled 3.
4. **Requirements to which there is an indifferent attitude**. Nobody thinks they are very important and nobody cares how well they are met because they are not important. Developing solutions for something in the lower left hand quadrant of Figure A4 and above the line labelled 1 is not productive and not cost-effective.

The top third and the bottom third of the requirements, based on their opportunity rank, were then plotted into a Kano diagram (Figure A5). The middle third of requirements were overlapping both red and yellow numbers and therefore have been left out of the diagram.

It can be seen that a large number of the requirements from the decadal plan survey process were ranked close together. To prioritise these requirements, further differentiation was needed. Therefore additional scoring and ranking was performed by the Decadal Plan Working Group on:

1. Urgency to implement effective solutions for each requirement (Score 1 very low urgency, 2 = low, 3 = moderately urgent, 4 high urgency and 5 = extremely urgent).
2. Ease of implementation of solutions for each requirement (Score 1 extremely difficult to implement, 2 = difficult to implement, 3 = moderately easy, 4 easy to implement, and 5 = very easy to implement).

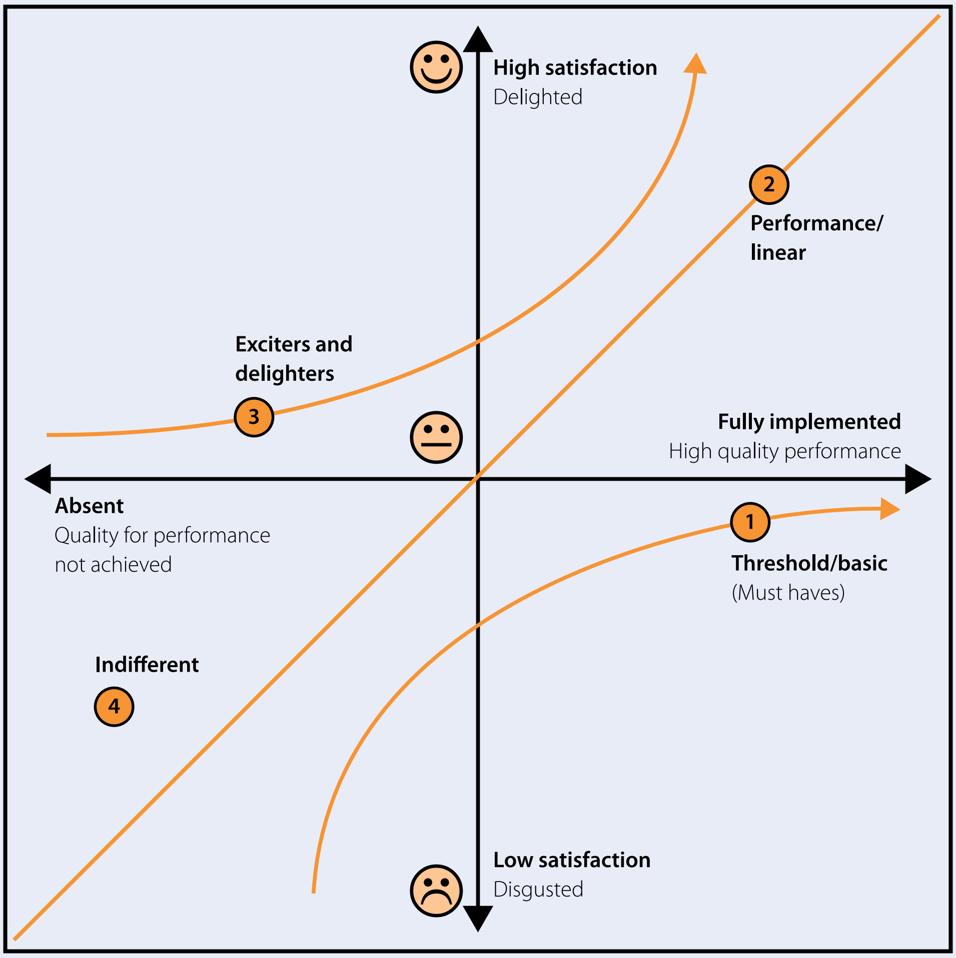
Note here that 'urgency' is not 'importance'! The degree of urgency reflect the need to act immediately to implement some action if we want it to succeed. Ease also reflects a new aspect to the process. There may be numerous things we can do with little resourcing or funding, but these actions may not resolve 'important' issues. For example, 'delighters' might be exciting and easy to implement but may not help the sector. An example might be getting a famous chemistry Nobel Laureate to come to Australia.

Plotting the top third, middle third and bottom third of the requirements (based on their opportunity index) into a new Kano diagram in which the vertical axis was the mean 'ease of implementation' index and the horizontal axis the 'mean urgency' index of each requirement, resulted in a wider spread of the requirements in the diagram (Figure A6).

In summary, to try and prioritise the 39 requirements identified by the chemistry sector, we have first ranked them in terms of 'importance' and 'satisfaction'. This allowed some

7 A good summary of how a Kano model is used in new product and service development can be found here: http://www.kanomodel.com/discovering-the-kano-model/

Figure A4: Typical Kano diagram



Source: Kano

to be discarded or lowered in priority. However, many requirements had similar rankings on this basis, which would make ultimate implementation difficult to carry out. By replotting the requirements in terms of their 'ease of implementation' and their 'urgency', better differentiation was possible.

These four characteristics can be combined into an overall 'attractiveness' index, based on the opportunity index, mean implementability and mean urgency of each requirement, hoping to find a best fit rank for each requirement that would ensure that all of the most important, urgent and currently poorly met requirements could be easily implemented, and that expenditure of effort and resources on hard-to-implement or less important requirements could be avoided.

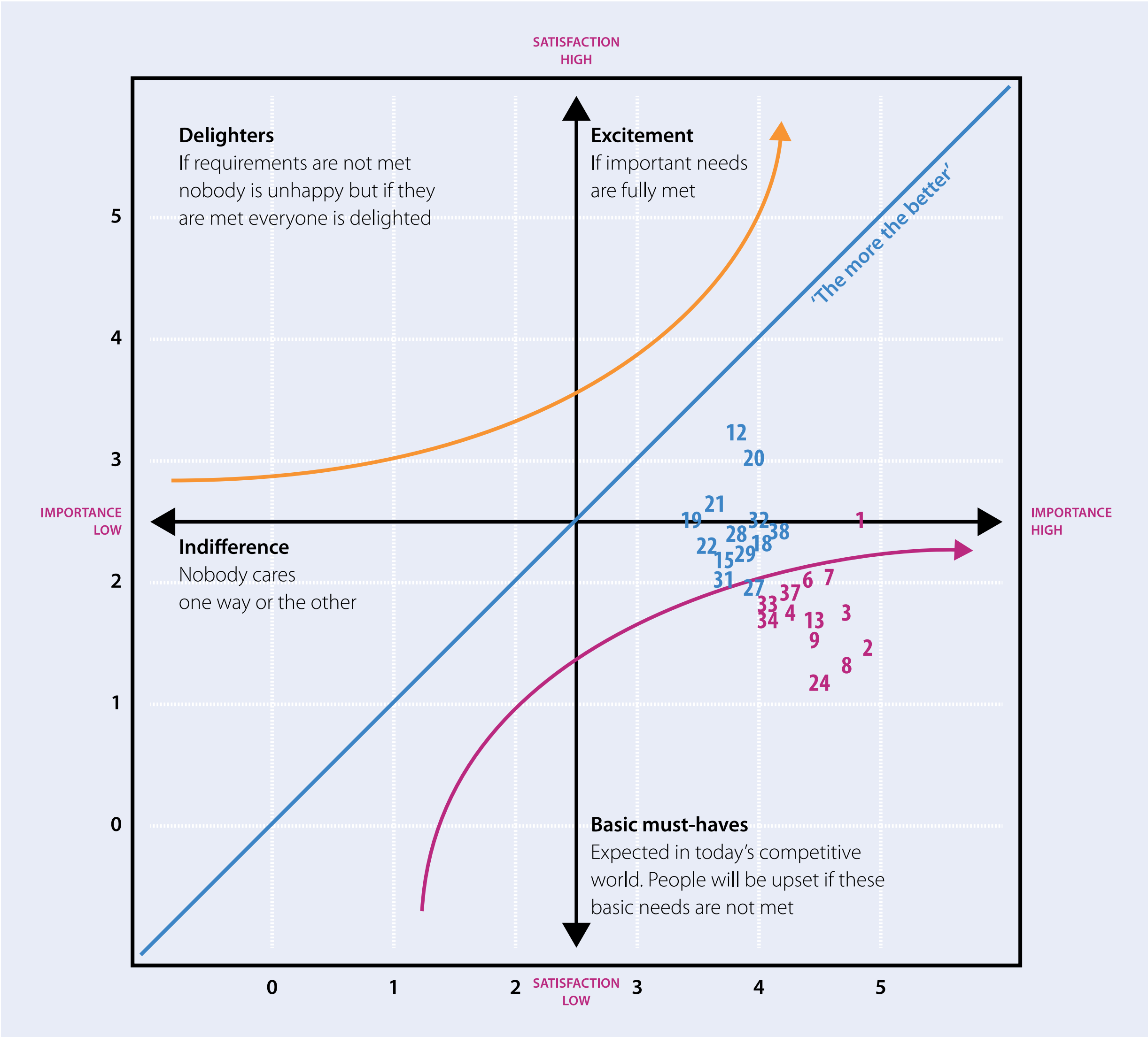
The full list of requirements with the numbering as shown in the Kano diagrams is provided as Appendix 9.

Strategy formulation

The decadal plan is fundamentally a bottom-up or grassroots document. It attempts to collect the experience, wisdom and insights of the experts and practitioners in the field and to get them to formulate the direction they believe will best serve Australia. It is hopefully clear from the methodology applied that the decadal plan provides the sector with a mirror. It is not a policy document being imposed from without, but an internal assessment of the sector's performance and aspirations.

The analysis of this information identified where current impediments in the interactions between the sectors is occurring. It also identified specific needs and specific requirements that need to be met to ensure that threats can be managed, new opportunities exploited and challenges and weaknesses overcome.

Figure A5: Kano diagram — We aim to identify all requirements that are either 'must haves' or which lie under the 'The more the better' performance line. This prioritises 'importance' over 'excitement'



From this analysis a number of strategic options were developed so that chemistry stakeholder requirements can be met and which further enable the Australian chemistry community and the overall value chain to adapt to the substantially changing global environment that will be operating over the next decade and beyond.

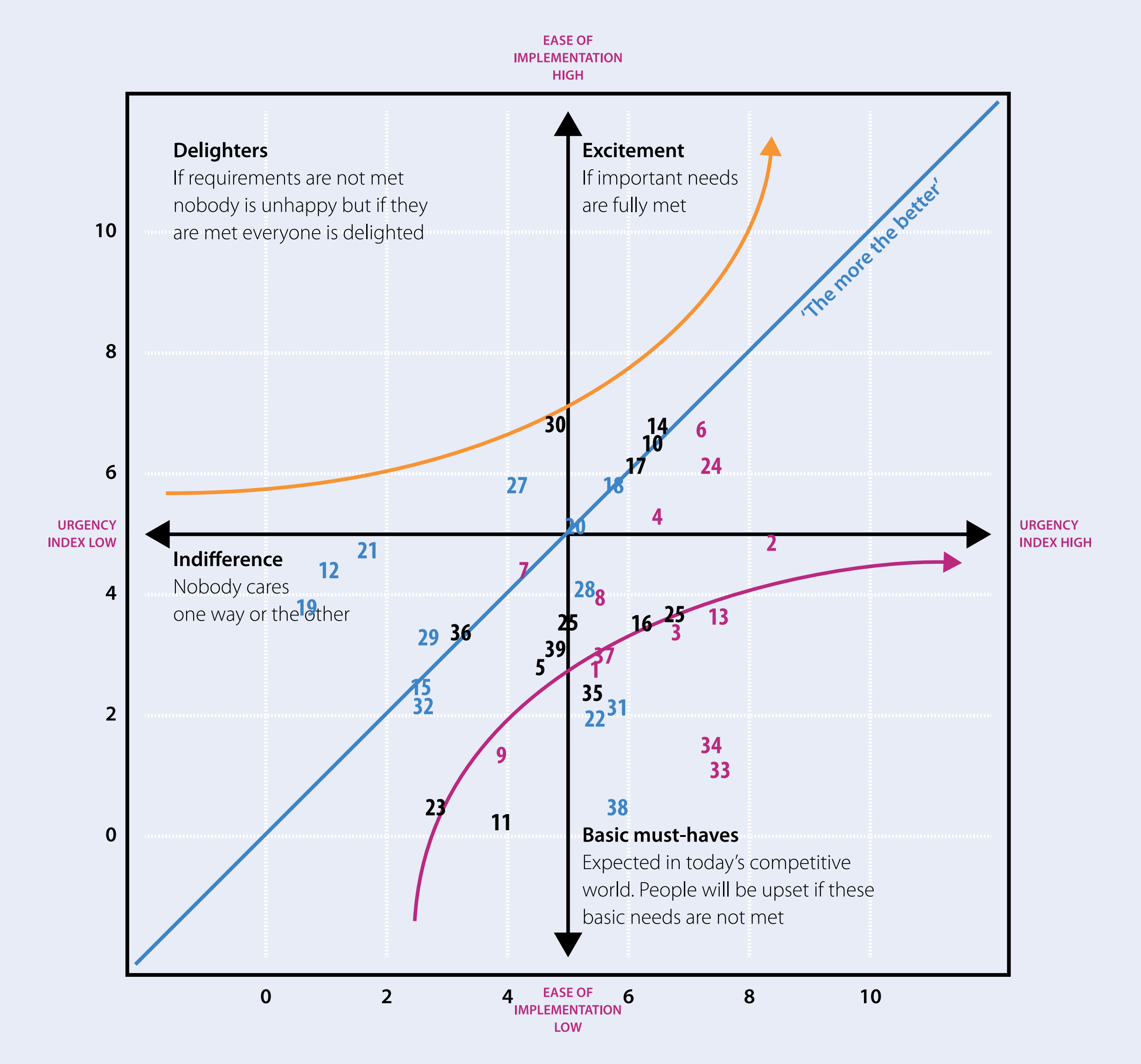
The number of strategic options is large but the decision of the decadal plan committee was to limit the number of strategic options to those that would be most 'attractive', that is, those that enable long-term efficient, viable and profitable outcomes that also have high impact and are efficacious. The major basis for deciding on the strategic options chosen was the speed and ease of implementation, the effectiveness of delivering results, the ability to increase efficiency to world's best practice, and the ability to adapt to future threats originating from existing and emerging megatrends.

Recommendations and the implementation process

The Decadal Plan Working Group made a small number of recommendations, based on the strategic options. However, in order to make recommendations, the strategic options were first evaluated in terms of their implementability and cost of implementation. If implementation of some of the options is too expensive for the current financial position of individual sectors of the value chain, or if the policy environment changes during the course of the coming decade, the strategic options need to be revisited.

The implementation process is addressed in Chapter VII of the decadal plan. It was based on a number of assumptions, the primary one being that the strategies, as defined in the decadal plan, will be implemented at some stage during the coming decade, but as early as possible.

Figure A6: Kano diagram yielding a wider scattering of the requirements but most 'must have' requirements are still 'must have' requirements despite their issues with low or moderate implementability



Appendix 6
Individuals interviewed and consulted during the interview process

1. Gary Smith, Senior Principal Engineer, URS Australia Pty Ltd
2. Peter Kouwenoord, Laboratory and Product Development Manager, LyondellBasell Australia Pty Ltd
3. Ross Pilling, Chairman and Managing Director, BASF Australia Ltd
4. Markus Ehrat, KTI Innovation Mentor, Magden, Switzerland
5. Nathan Fabian, CEO Investor Group on Climate Change
6. Thomas Kerr, Director Climate Change Initiative, WE Forum
7. Wayne Best, Managing Director, Epichem Pty Ltd
8. Amanda Graystone, chemistry teacher, Nossal High School, Victoria
9. Brendon Graystone, PhD candidate Monash
10. Trevor Hambley, Dean of Science, University of Sydney
11. Naomi Bury, undergraduate science student
12. Merion Harmon, primary school teacher, Northern Bay College, Corio Victoria
13. Deanna D'Alessandro, Dept of Chemistry, University of Sydney
14. George Carydias, Chemical Engineer, RMAX Australia
15. Gerry Wilson, CSIRO
16. Gwen Lawrie, Head of 1st Year Program, School of Chemistry and Molecular Biology, University of Queensland
17. Andrea O'Connor, Chemical Engineering, University of Melbourne
18. Andrew Pascoe, science teacher, Ceduna
19. Phil Davies, Senior Research Leader, DST Group
20. Ravi Naidu, CEO of the CRC CARE, Adelaide
21. Paul Donnelly, Senior Lecturer, School of Chemistry, University of Melbourne
22. Robert Schofield, teacher, NSW
23. Graeme George, Polymer Chemistry QUT
24. Lawrence Meagher, CSIRO
25. John Cerini, CEO Integrated Packaging
26. Chloe Munro, Chair, Clean Energy Regulator
27. Clinton Foster, Geoscience Australia
28. John Gunn, CEO, AIMS
29. Jane Cutler, NOPSEMA
30. Brian Richards, Department of Health, NICNAS
31. Paul Grimes, Dept of Agriculture and Water Resources
32. Michelle Baxter, Worksafe Australia
33. Jonathan Palmer, Australian Bureau of Statistics
34. Adrian Paterson, CEO, ANSTO
35. Alex Zelinsky, DST Group
36. Rob Vertessy, CEO, Bureau of Meteorology
37. Rosanna DeMarco, Dow Chemicals
38. Patrick Houlihan, Dulux
39. Lauren Reader, University of Melbourne
40. Greg Chow, University of Melbourne
41. Mick Moylan, Chemistry Outreach Program, University of Melbourne
42. Rose Amal, Head of School of Chemistry, UNSW Australia and Director of the ARC Centre of Excellence for Functional Nanomaterials
43. Cameron Shearer, postdoc, Flinders University
44. Deanna D'Alessandro, Lecturer, School of Chemistry, University of Sydney
45. Max Massi, Senior Lecturer, Dept of Chemistry, Curtin University
46. Angus Netting, MD, Adelaide Microscopy
47. Mr Nigel Brookes, science teacher, Guilford Young College, Tasmania
48. Richard Muscat, DST Group Melbourne
49. Shaun Smith, Project Manager, CSIRO
50. Brett Roman, GHD Australia
51. Katrina Frankcombe, The Garvan Institute
52. Mike Pointon, Manager Innovation & Development, Nufarm
53. Dana Johnson, CSIRO AAHL
54. Phillipa Pearce, Teesdale Primary School
55. Jacinta Branson, Geelong College
56. Christopher Gulle, St Joseph's College, Newtown, Victoria
57. Andrew Gulle, Welder, Bamganie, Victoria
58. Sandra Haltmayer, Steinbeis GmbH Suttgart, Germany
59. Uwe Haug, Steinbeis GmbH, Stuttgart, Germany
60. Meron Southall, primary school science teacher, Teesdale Primary School, Victoria
61. Tony Gove, Principal, Teesdale Primary School, Victoria
62. Chris Such, Research Manager, Dulux Australia

63. Philip Leslie, Site Technical Lead, GlaxoSmithKline Australia
64. Jenny Sharwood, retired
65. Ian Dagley, CEO, CRC for Polymers
66. Danielle Kennedy, CSIRO
67. Sean Murphy, University of Melbourne
68. Uta Wille, University of Melbourne
69. Robert Robinson, ANSTO
70. Richard Thwaites, retired
71. Curt Wentrup, University of Queensland
72. Fabien Plisson, University of Queensland
73. Megan Cook, Department of Health, Queensland
74. Peter Karuso, Macquarie University
75. Andrew Mariotti, teacher
76. David Edmonds, RACI
77. Leonie Walsh, Victorian Lead Scientist

Appendix 7
Locations and dates of town hall meetings

Public town hall meetings were held at 26 locations across Australia as part of the stakeholder consultation process.

	Town hall Meeting	Date (2014)	Location
1	CONASTA Conference	9 July	Adelaide
2	University of Melbourne	29 July	Melbourne
3	Flinders University, South Australia	19 August	Adelaide
4	University of Technology Sydney	20 August	Sydney
5	Monash University	20 August	Melbourne
6	University of Sydney	27 August	Sydney
7	ANSTO	28 August	Lucas Heights, NSW
8	UNSW Australia	28 August	Sydney
9	Women in Chemistry meeting? conference?	2 September	Melbourne
10	South Australia RACI Branch Meeting	15 September	Adelaide
11	University of Queensland	15 September	St Lucia, QLD
12	SETAC Asia–Pacific 2014	16 September	Adelaide
13	Charles Darwin University	22 September	Darwin
14	CSIRO – Clayton	9 October	Melbourne
15	Charles Sturt University	10 October	Wagga Wagga, NSW
16	Industry Forum on The Future of The Chemical Industry In Australia	14 October	Brisbane
17	University of Adelaide	14 October	Adelaide
18	Curtin University	22 October	Perth
19	University of Western Australia	31 October	Perth
20	Queensland University of Technology (QUT)	6 November	Brisbane
21	Griffith University	13 November	Griffith, NSW
22	BioMelbourne Network Breakfast: 'Future of Chemistry, Future of Manufacturing'	25 November	Melbourne
23	University of Wollongong	25 November	Wollongong, NSW
24	QUT – STAQ Annual Workshop – A Forum for Qld Chemistry & Science Teachers	28 November	Brisbane
25	Australian National University	4 December	Canberra
26	RACI National Conference	8 December	Adelaide
27	James Cook University, Townsville and Cairns (via Weblink)	9 December	Townsville and Cairns, QLD

Appendix 8
Organisations consulted

Universities

University of Melbourne

University of Queensland

Monash University

University of Sydney

University of Wollongong

UNSW Australia

Australian National University

Flinders University

Curtin University

University of Western Australia

Griffith University

Education providers

Science Teachers Association of Queensland (STAQ)

Science Teachers Association of Victoria (STAV)

Conference of Australian Science Teacher Association (CONASTA)

Research institutions

CSIRO

Australian Nuclear Science and Technology Organisation (ANSTO)

Defence Science and Technology (DST) Group

The Australian Synchrotron

Melbourne Centre for Nanofabrication

Industry organisations

Dulux-ICI

CRC for Polymers

The BioMelbourne Network

Plastics and Chemicals Industries Association (PACIA)

Other lead organisations

Royal Australian Chemical Institute (RACI)

Women in Chemistry

Australian Academy of Technology and Engineering (ATSE)

Government organisations

The Office of the Victorian Lead Scientist

The Office of The Chief Scientist

Sponsors

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- the Australian Research Council, through its Learned Academies Science Policy (LASP) program
- the Australian Academy of Science
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- The Royal Australian Chemical Institute (RACI).

Appendix 9
List of requirements

From the analysis of the town hall meetings, interviews, and submissions, a set of requirements were drawn up that were ranked using the process outlined in Appendix 5.

Rank #	Requirement / Desired outcome or solution	Mean importance (0–5)	Mean satisfaction (0–5)	Opportunity index (1–10)
1	**GOV R2**: Australia needs to adopt world's best practice in science policy making at all government levels	4.9	1.5	8.3
2	**GOV R8**: Australia needs more science-literate leaders, policy makers and advisors in government, who can better understand technology driven change in industry and society	4.7	1.3	8.1
3	**GOV R24**: The allocation of research funds to research institutions needs to be simplified to reduce the currently substantial time overhead for grant application writing	4.5	1.2	7.7
4	**GOV R3**: Australia needs to be pro-active in adopting successful models of innovation policies, strategies and schemes from countries that are leading the innovation rankings	4.7	1.8	7.5
5	**EDU R13**: The gaps in science literacy of primary school teachers needs to be addressed as a matter of urgency to prevent students' curiosity and interest in science from declining prior to entry in high school	4.5	1.7	7.3
6	**ALL R9**: The science literacy of the Australian general public needs to be upgraded to facilitate informed and better public debate on global issues that require the input of chemistry science for effective solutions	4.5	1.7	7.2
7	**ALL R7**: The chemistry community collectively needs to take on the responsibility for the way chemistry is portrayed to the general public and in the media and to work on ways to improve the public perception of chemistry	4.5	2.0	7.0
8	**IND R1**: Australia needs to adopt world's best practice in industry processes in the chemical industry and industry sectors that require substantial chemistry knowledge	4.7	2.6	6.9
9	**ALL R6**: All segments of the Australian chemistry community need to develop a unified collaborative approach for overcoming the causes and impacts of Chemistry illiteracy and poor image	4.4	2.0	6.7
10	**GOV R37**: Government-funded agencies need to develop shorter response times in their interaction with industry companies so that negative impacts on business competitiveness are reduced	4.3	1.9	6.7
11	**GOV R4**: Australia must implement existing highly effective innovation schemes and mechanisms from leading innovating countries if they can be implemented at low cost or cost-neutral in Australia	4.3	1.9	6.6
12	**GOV/IND/RES R33**: Chemistry research translation mechanisms (from research to commercial development) need to be developed that are viable and advantageous for all participants in an environment of limited industry profitability and limited government support	4.2	1.9	6.5
13	**GOV/IND/RES R34**: The current difficulties of access to translational opportunities for proof of concept from research to large-scale chemistry industry development needs to be addressed	4.2	1.9	6.5
14	**GOV/IND/RES R35**: Solutions must be developed for the problems of getting a higher number of start-ups off the ground in the chemical space	4.1	1.8	6.4
15	**EDU R14**: Engaging chemistry teaching materials need to be developed that are easily accessible by schools and teachers in all schools including remote, rural and economically disadvantaged schools	4.3	2.2	6.4

Rank #	Requirement / Desired outcome or solution	Mean importance (0–5)	Mean satisfaction (0–5)	Opportunity index (1–10)
16	**IND/RES R25**: New, effective and affordable models for R&D collaboration between chemical industry companies and research providers need to be developed to enable collaboration in a cash-poor operating environment	4.1	1.9	6.4
17	**HER/EDU R10**: Chemistry education models and engaging materials need to be developed that help teachers to deliver improved educational and chemistry literacy benefits to children of all ages and backgrounds (i.e. from pre-school to year 12)	4.4	2.5	6.3
18	**RES/GOV R26**: The capabilities of Australian research providers must be strengthened substantially to enable them to become the preferred R&D partners for both Australian and international companies who seek high-end innovation	4.3	2.4	6.2
19	**EDU/HER R16**: As a matter of urgency professional development mechanisms must be developed for chemistry (science) teachers in regional and remote locations	4.0	1.9	6.2
20	**EDU R11**: Age-specific and engaging teaching and learning models need to be implemented that do not exclude disadvantaged children but instead lift their participation in science and chemistry and their educational outcomes	4.2	2.3	6.2
21	**RES R30**: More balanced reward and promotion mechanisms in research organisations must be developed that do not disadvantage commercial activity and creation of patentable IP	4.1	2.1	6.2
22	**IND/RES/GOV R39**: There need to be better, more flexible models for cost recovery that facilitate the development of new chemical products to balance the upfront costs of R&D investment in new product development	4.1	2.0	6.2
23	**GOV R36**: Government agencies need to develop a more education focused and collaborative rather than an adversarial mode of interaction with Australian industry companies	4.1	2.2	6.1
24	**RES/IND R5**: Research data from Australian research providers (e.g. universities, CSIRO) need to be analysed regularly in a systematic manner to identify potential technologies that could be translated into new products and processes with appropriate support	4.0	2.0	6.1
25	**HER/IND R17**: Engaging information material needs to be developed for parents and middle school students that provide information on the types of employment pathways that a solid chemistry education in secondary school would facilitate in the future	4.1	2.2	6.1
26	**RES R23**: To improve research efficiency and effectiveness, the Australian research sector has to develop increased skills, strategies and better mechanisms that are not solely reactive to the government policies of the day	4.1	2.2	6.0
27	**HER/EDU/IND R18**: Up-to-date and better information must be made available to high school teachers and higher education providers about chemistry-related future job market developments to enable adaptation of teaching to future needs	4.0	2.2	5.9
28	**RES R27**: Australian research providers need to actively and routinely provide information about their research capabilities, research equipment, and research services to chemical companies and companies in other industry sectors to facilitate appropriate R&D partner selection by industry	4.0	2.1	5.8
29	**HER R31**: Higher education providers must develop distinct programs that cater for different career pathways (academic; industry and teaching) to prevent overcrowding of the academic pathway with consequent poor career prospects and inadequately equipped graduates for industry and teaching	3.9	2.1	5.8

Rank #	Requirement / Desired outcome or solution	Mean importance (0–5)	Mean satisfaction (0–5)	Opportunity index (1–10)
30	**GOV/EDU R15**: The chemistry knowledge requirements for achieving the basic skills needed by the technically oriented workforce of the future need to be determined to ensure school leavers of the next decade and beyond are equipped with the necessary chemistry knowledge regardless of their background situation or location	4.0	2.2	5.8
31	**GOV R38**: There needs to be better harmonisation, simplification and transparency of regulation in the chemistry space to facilitate better compliance and quicker realisation of benefits from commercialisation of new chemistry based research	4.1	2.4	5.8
32	**RES/GOV R29**: New metrics for chemistry research efficiency and effectiveness need to be developed that provide a more balanced picture of a research provider's level of excellence in the international context than just publication focused metrics	4.0	2.2	5.8
33	**HER R32**: New higher education models are required for providing chemistry graduates and postgraduates with the skill sets demanded by the industries of the future	4.0	2.5	5.5
34	**RES R28**: Australian research institutions need to abandon their focus on safe, run-of-the-mill chemistry research areas in favour of more high risk, strategic work that can become the source of future innovation	3.8	2.4	5.1
35	**HER R20**: Chemistry graduates (esp. MSc and PhD) need to have more transferable skills, to enable flexibility. These include generic maths skills and problem solving skills	4.0	3.0	5.1
36	**HER R22**: Graduates and post-graduates need to include more practical industry experience during their studies to enable them to be more effective as industry employees	3.6	2.2	5.1
37	**HER R21**: Universities need to develop a more flexible approach to teaching chemistry to enable fast adaptation to the needs of new and more cross-disciplinary professional pathways	3.7	2.6	4.8
38	**HER/IND R19**: To be attractive to the demanding employers of the future in all sectors graduates need to have cross-disciplinary expertise, such as in biology, engineering, toxicology, physics or earth science etc.	3.6	2.5	4.7
39	**GOV/RES R12**: The reasons for and the benefits of adhering to work health and safety regulations need to be better communicated throughout the chemistry community and especially the research sector	3.9	3.2	4.7

Appendix 10
Considerations and guidelines for a decadal plan implementation plan

An implementation plan is an essential part of a business plan such as this Chemistry Decadal Plan. It consists of a proposed sequence of implementation steps that takes into consideration interdependencies between the various steps that need to be implemented, as well as a list of the assumptions made while developing the implementation plan. This is a common practice in business and it can be readily extended to the chemistry implementation plan.

Preliminary dependency analysis of the strategic structure of the decadal plan

Initial scoping work has been conducted to help identify interdependencies between strategies and to identify critical clusters in the value chain. Dependency Structure Matrix Analysis methods[8] were used to:

8 Eppinger, S.D. and T.R. Browning (2012) Design Structure Matrix Methods and Applications, Cambridge, MA: MIT Press.

1. Define those groups of strategies and sub-strategies that are connected via dependencies in a modular form. For this dependency analysis, a clustering algorithm was used that aggregated those strategies into clusters that had the most interdependencies within the cluster and few outside the cluster. The visual arrangement of these clusters allowed different groups of people with appropriate skills to be identified, who would be best placed to develop budgets and drive the tasks that need to be accomplished to ensure that the strategies within the cluster are implemented efficiently and efficaciously.
2. Define the optimal sequence of implementation steps, by identifying which strategic outputs need to be used as inputs into other strategies. The strategies were then sorted, with those having the fewest dependencies being allocated to the beginning of the implementation process, and those that depend on the outcomes from other steps being pushed back to the end of the implementation process. The required resources, cost and effort for each strategy implementation task were then determined and finally, a schedule was constructed together with an overall implantation budget.
3. Identify those 'blocks' of strategies that may require special consideration because of extensive interdependencies and potential for likely iteration.

Cluster analysis

Cluster analysis revealed five implementation clusters around the following activities:

1. Establishing the implementation committee and its working budget, KPIs, TORs, funding, and issues involved with further iteration, i.e. adjustment of the strategic direction after acceptance of the decadal plan.
2. Recalibrating the education of chemistry, both in the school and the higher education sectors. Due to the many interdependencies between both the school sector and the higher education sector, the analysis found that there should be a common implementation module with a working group that spans both sectors.
3. Improving the working relationship between industry and the research sector. Parts of this implementation module include (i) the development of a common value chain roadmap and R&D plan, (ii) a drastic enhancement in the range and depth of interactions of research providers with industry and (iii) establishment of an innovation mentorship scheme. The implementation of this module requires a working group with specialised skill sets, i.e. with expertise across both industry and research sectors, as well as appropriate industry and government membership.
4. Improving research efficiency through clearer priorities, infrastructure productivity increases and a risk balanced research portfolio.
5. Developing a media strategy and a chemistry expert access program. This smaller module requires very specific expertise and highly developed networks across the Australian chemistry stakeholder community.

The grouping of strategies within the clusters does not mean that all of them need to be implemented in the sequential order listed above. They can be addressed, or at least started, simultaneously if the necessary expertise can be assembled quickly and funding is made available. While the initial analysis found significant clustering, a full implementation plan detailing human resource requirements and operating budgets for addressing these five strategic modules should be created early on by the Implementation Plan Committee.

Sequencing analysis

The next stage of the analysis involves re-ordering the list of decadal plan strategies in order to arrive at an optimised order for implementation.

The order in which strategies should be implemented is probably not surprising. However, a number of tasks are highly interdependent and therefore there is a high chance of unplanned iteration that can potentially lead to failure. For example, in interactions between research providers and industry partners, such potential impediments include whether the research portfolio has an appropriate risk-balance ratio, the likely speed of research output delivery and the probability of successful research outcomes. Each aspect can hold research translations back. Any new translation models need to be structured to account for these factors.

In this particular case, generating a new translation model could be achieved by having two smaller working groups. One of these two groups could focus on research translation and incentivising interactions, while the second group would focus on research process, efficiency and priority development. The major point here is that while many sectors of the chemistry stakeholder community would like to have better translation models, setting these up is a non-linear process and the process itself will depend on the outcomes of other Implementation Committee deliberations.

Key implementation linchpins, risks and dependencies

Implementation of the decadal plan strategies needs to take into account the interdependencies between the recommended strategies. There are clear and specific linchpins in the strategic framework that need to be implemented thoughtfully, efficiently and effectively because of the many other strategies that depend on their effective implementation. These linchpins, if not implemented successfully, will represent substantial risks to the success of the decadal plan.

The two most critical strategic linchpins are (1) the development of a common roadmap with a rolling

R&D plan that supports successful adaptation and response of chemistry research, teaching and industry to emerging threats, challenges and opportunities, and (2) the appointment of a decadal plan implementation committee with suitably qualified members who are able to work towards common goals.

Two substantial risk areas are (1) getting agreement by research providers and industry on a risk-balanced research portfolio and (2) eliminating research translation hurdles. If agreement on new and mutually beneficial price/cost models cannot be developed, collaboration between the research sector and industry will not succeed.

A third area of risk is the ability to reach agreement on education goals in the primary, secondary and tertiary education sector. This will depend on buy-in by other stakeholder sectors, and especially by industry.

The other strategies which have a number of dependencies and that require new thinking, operations and models are mainly in the higher education and research provider sectors. However, these strategies will require guidance by, and interaction with, the government sector.

This brief analysis of the structure of the strategic framework and the potential issues likely to be encountered during implementation needs to be substantially expanded to derive a 'bankable' implementation plan.

The key risks of this decadal plan lie in the ability of the chemistry stakeholder sectors to come together and work with a suitably qualified and motivated implementation committee towards, firstly, a common roadmap, and secondly towards lifting the effectiveness and efficiency of all the chemistry stakeholder sectors towards making larger contributions of the chemistry discipline possible for a more competitive national economy.

Appendix 11
Pilot scheme for R&D project mentorship for chemical SMEs

The decadal plan contains a recommended pathway for implementing a pilot program for enabling chemical industry companies, and especially SMEs, to facilitate faster innovation and increased competitiveness of the sector via faster development of more high-end products, processes and services. This recommendation is based on the scheme delivered through the Swiss Commission for Technology Innovation (CTI) model.[9]

Objectives of the CTI

The CTI aims to generate more innovative products and services by motivating higher education institutions and the private sector to carry out application-oriented R&D projects together. Hundreds of such projects are supported every year.

The CTI provides funding for projects based on the following principles:

- Project partners define their own projects.
- Projects contribute to establishing Switzerland as an investment grade centre for business and research, and improve the competitiveness of the economy.

Companies benefit from the expertise of young, trained researchers, and access to the infrastructure of the higher education institutions for their projects. Project grants are open to all disciplines and assessed by relevant experts in four main subject areas. Approved projects demonstrate the greatest potential for knowledge generation and added value.

Scheme funding supports the salaries of around 1,000 researchers each year. The CTI generally pays just for the research institution salaries and some related research costs in the research institution. The company is expected to pay at least 50% of the project costs (including cash and in kind costs).

Eligible research facilities/partners for R&D projects

- Higher education and research sector
- ETH Domain (Technical higher education institutions)
- Non-commercial research facilities outside the higher education sector (recognised by the CTI)

How to apply for an R&D project

The application process has eight steps:

- Step 1: Compose your project team
- Step 2: Find out more about your research topic
- Step 3: Develop a project plan
- Step 4: Submit the application

9 R&D projects for your company. https://www.kti.admin.ch/kti/en/home/unsere-foerderangebote/Unternehmen/f-e-projekte.html

- Step 5: Application processed
- Step 6: Decision
- Step 7: Statutory requirements
- Step 8: Sign the contract.

In Step 1, it is possible for a company that already has an idea for technology innovation to submit an application for an R&D project. However, if the company has an idea and not yet developed connections with a research organisation but wants to get started, it can apply for a CTI voucher,[10] which gives companies the opportunity to submit a research and development project funding application without specifying a research partner. This is particularly important for SMEs that want an expert assessment of their innovation project and help with looking for a research partner.

It is also possible for a company that has limited experience with R&D and/or no specific project ideas to get started by submitting an application for an innovation cheque (CHF 7,500 for one year). This funding supports initial interactions with research providers for feasibility testing of ideas. Innovation cheques contribute to the costs incurred by the research partner for services provided, i.e. salaries, material costs, travel expenses.[11, 12]

Once a project is approved, the company is responsible for driving its completion as quickly as possible and according to milestones. An implementation audit is conducted 18 months after the end of the project to assess the value created through the project.

The two key requirements for the successful implementation of this scheme are:

- an expert panel for the research area in which the application is submitted
- innovation mentors.

Expert panels

Each of the main innovation areas has an expert panel that, on a monthly basis, assesses applications for innovation cheques, vouchers and R&D projects.

Each panel is composed of between 12 and 15 experts from Swiss industry and the research sector.[13]

Innovation mentors

The innovation mentors (IMs) help companies and public research institutions to jointly launch science-based innovation projects of national and international significance. IMs inform companies of the funding opportunities open to them and help them to draw up CTI project proposals. The mentors also facilitate cooperation between companies and public research institutes in science-based innovation projects of national and international importance.

The service provided by IMs is directed primarily at R&D-based, innovation-oriented businesses. Their services are provided free of charge to the company and are paid by CTI.

IMs, with innovation expertise gained in R&D-heavy commercial companies, are able to answer the following questions for a company that wants to embark on an innovation project[14]:

- Our company has an innovative idea but we are lacking in research expertise. Where and how do we find this?
- Who can give me an overview of the different funding institutions for innovation projects?
- Which research institution would be the best partner for my innovation project?
- Does my project have a chance of attracting CTI R&D funding?
- Is my company actually eligible to receive CTI funding for innovation projects?
- What factors are involved in successfully launching my innovation on the market?
- Are then any contractual agreements between me and my research partner?
- How do I draw up a project application for the CTI and how do I sort out patent issues with my contractual partner?

The qualifications and experience of Swiss IMs are very high.[15] The main focus is on having long-term, in-depth expertise in higher positions in the commercial sector in R&D-focused companies that have a track record of bringing products and services to the market in reasonable time frames and creating substantial revenue for the companies they worked for. They have to be independent and respected by both the SME sector, larger companies, the research sector and government agencies.

Consequently, most of the Swiss IMs are older than 50, with a mix of experience with major industry companies and with spin-out start-ups. All current Swiss IMs work in the commercial sector and not in government or in the research provider sector. The major difference between Swiss IMs and Australian innovation support specialists is the much longer and in-depth technology/new product development expertise in multinational and large companies.

10 CTI Voucher: submit an application without a research partner.
11 Innovation cheques for SMEs. file:///C:/Users/Elke/Downloads/General%20conditions%20innovation%20cheque.pdf
12 Innovation cheque flow chart. file:///C:/Users/Elke/Downloads/Process%20innovation%20cheque.pdf
13 KTI-Expertenteams 2014. file:///C:/Users/Elke/Downloads/M_Expertenliste_F&E_2014_de.pdf

14 Innovation mentors: partner and support for your business. https://www.kti.admin.ch/kti/en/home/unsere-foerderangebote/Unternehmen/beratung--innovationsmentoren.htmlind
15 Anforderungsprofil KTI Innovationmentor/in (IM). file:///C:/Users/Elke/Downloads/Profile%20innovation%20mentor%20(in%20German)%20(1).pdf

Costs of the Swiss CTI funded R&D and Innovation Mentorship scheme

The Swiss system is heavily SME focused. Of the 553 commercial companies receiving R&D support via the CTI, 71% are SMEs and in 2014, 54% of the companies were involved with the scheme for the first time.

Funding to the research sector for the research projects under this scheme totalled CHF 117.1 million for a total of 362 R&D projects to which industry contributed CHF 141.2 million.

On average, the expenditure by the CTI for an R&D project under this scheme is estimated at CHF 335,000 per annum for a new project.

The research mentorship scheme expenditure (13 innovation mentors) for support of the industry-research provider interaction was CHF 1 million in 2014, plus CTI support for the mentorship scheme.

Proposed Australian innovation mentorship pilot program

As part of the strategic goal 3 of 'Raise the level of research and innovation efficiency and improve the translation of research results', this plan recommends the implementation of a pilot innovation mentorship program for facilitating better and more targeted technology transfer between the chemistry research community and industry (and especially SMEs).

The proposal is for the program to provide access to two innovation mentors (one in biotech/biosciences/agricultural etc chemistry, and one in the petrochemical based/mining chemistry based backgrounds), preferably with chemical engineering knowledge or links to chemical engineering.

They should be based in a location where the chemistry industry has some critical mass in these areas, with both large companies and SMEs being established in large enough numbers and connections to one or more relevant chemistry industry growth centres and high-end research infrastructure.

Benefits of an innovation mentorship program

The expected benefits of the innovation mentorship program include the following:

- A critical mass of new young and trained research scientists will be employed on industry projects. These researchers would otherwise not be exposed to industry research and especially the innovation needs of SMEs.
- SMEs will be trained in R&D and new product development by innovation mentors who have substantial expertise in both industry R&D and new product development, as well as with the global and national chemical industry and innovation landscape.
- The hurdle that SMEs see in not being able to afford research scientists' salaries will be broken down. They will be able to afford the R&D project as the research scientist salary expenditure is paid directly by the mentorship scheme to the research institution.
- Closer connections and interactions between industry and the research sector will be formed that contribute to a more seamless collaboration between the two sectors.
- The level of SME R&D efficiency and innovation capability will be raised.
- The level of R&D provider research efficiency and research translation capabilities will be raised.
- Existing manufacturing capabilities of the Australian industry landscape will be leveraged through increased focus on science-based product, process and service innovation. This will add value to the Australian economy once this pilot scheme has been successfully implemented as a viable innovation model.

Appendices 12 to 15 in Part 2 of the Chemistry Decadal Plan

Appendices 12 to 15 are provided as Part 2 of the Chemistry Decadal Plan, for download from the website **https://www.science.org.au/node/2178**

Appendix 12: Town Hall meeting summary

Appendix 13: Current issues, critical success factors and opportunities for the future

Appendix 14: Survey results—chemistry teachers

Appendix 15: Survey results—chemists in government

List of Abbreviations

AFFRIC	Australian Future Fibres Research and Innovation Centre
ANFF	Australian National Fabrication Facility
ANSTO	Australian Nuclear Science and Technology Organisation
APVMA	Australian Pesticides and Veterinary Medicines Authority
ARC	Australian Research Council
ATSE	Australian Academy of Technology and Engineering
CEO	Chief executive officer
CFC	Chlorofluorocarbon
CO_2	Carbon dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTI	Commission for Technology Innovation
DDT	Dichlorodiphenyltrichloroethane
DECHEMA	DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V. (Society for Chemical Engineering and Biotechnology)
DNA	deoxyribonucleic acid
DST Group	Defence Science and Technology Group
E7	Group of 7 emerging economies
EPA	Environment Protection Authority
EU	European Union
FTE	Full-time equivalent
G7	Group of 7 advanced developed economies
GFC	Global financial crisis
IMBL	Imaging and medical beamline
LED	Light-emitting diode
MCN	Melbourne Centre for Nanofabrication
NHMRC	National Health and Medical Research Council
NICNAS	National Industrial Chemicals Notification and Assessment Scheme
OECD	Organisation for Economic Co-operation and Development
OH&S	Occupational health and safety
OPAL	Open Pool Australian Lightwater
PACIA	Plastics and Chemical Industries Association
PISA	Programme for International Student Assessment of the OECD
RACI	Royal Australian Chemical Institute
R&D	Research and development
SME	Small and medium enterprise
STEM	Science, technology, engineering, mathematics
TAFE	Technical and further education
TGA	Therapeutic Goods Administration
TIMSS	Trends in International Mathematics and Science Study
UK	United Kingdom
US	United States
VCAMM	Victorian Centre for Advanced Materials Manufacturing
WEF	World Economic Forum
WHS	Work health and safety