Australia's National
Science Agency

Hydrogen Research, Development and Demonstration

Priorities and opportunities for Australia

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CSIRO acknowledges the Traditional Owners of the lands that we live and work on across Australia and pay their respect to Elders past, present and emerging. CSIRO recognises that Aboriginal and Torres Strait Islander peoples have made and will continue to make extraordinary contributions to all aspects of Australian life including culture, economy and science.

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Chief Executive Foreword

Australia's economic prosperity and energy security will depend on us solving national challenges to follow the global market trend towards zero emissions energy. Australia is blessed with vast energy resources, many of them renewable, but some of our biggest trading partners are not so fortunate and are grappling with how to transition from a reliance on imports to lower-emissions alternatives. This is where science can unlock a seemingly impossible challenge, because hydrogen energy could both fill the gap in our export dollars and help the world navigate this energy market transition.

Australia can become a renewable energy superpower through the production and export of hydrogen, but it isn't easy to invent a new industry around an existing one. The past 18 months have seen unprecedented support for hydrogen, and with good reason. It has a role to play across transport, power, and industrial sectors, and is experiencing increasing domestic and international demand – especially when made from renewable energy. But hydrogen requires a fundamental paradigm shift – and we know that paradigm shifts are often the undoing of new technology. This is where science, as the great former Australian Prime Minister Billy Hughes said, "can lend a most powerful aid."

This report builds on the concepts introduced in our National Hydrogen Roadmap to identify five key hydrogen industry breakthroughs where research, development and demonstration (RD&D) can develop the Australian and global hydrogen industry. By focusing on these unfair advantages for Australia, we can bring together industry, government, and research organisations to de-risk technologies and catalyse industrial demonstration of critical elements, linking Australian activities with international projects.

Our goal is to fast-track the deployment of emerging hydrogen technologies, providing a means for industry to undertake the technical work required to help them transition to a new energy future.

National leadership is critical to connect key players and capabilities across the value chain, and as Australia's national science agency, CSIRO is partnering with key stakeholders like the Australian and Victorian governments, Origin, Woodside, BHP, and the Australian Renewable Energy Agency (ARENA) to frame this dialogue and develop a path for hydrogen in Australia through this report, as well as in a range of specific projects with partners like Toyota, Hyundai and Fortescue.

Science has already broken one of our major roadblocks by enabling seamless conversion between gaseous hydrogen and liquid ammonia using our patented hydrogen cracker. This simplifies storage and transport and leverages existing liquid fuel infrastructure. We've also invested in other key breakthroughs of the future through our Hydrogen Energy Systems Future Science Platform (FSP), de-risking new hydrogen technologies and supporting development of new energy markets including in chemicals and transportation sectors.

CSIRO has been forming collaborative networks around national missions for over a century and is now rallying partners to do the same for hydrogen. We can focus RD&D and bring together industry, government, and other research organisations in an initiative that will facilitate the development of industrial-scale, export-focused hydrogen value chains for Australia. This work will de-risk technologies and catalyse industrial demonstration of critical elements, and link Australian activities with international projects. It will fast-track the deployment of emerging hydrogen technologies developed by CSIRO and its partners.

We believe that building this new industry will focus all our energy on building a better future rather than arguing about the past – that's the power of national missions. Together, we can build a robust and innovative domestic and export hydrogen industry to power a brighter energy future for Australia.

Dr Larry Marshall
Chief Executive
CSIRO

1 Introduction: Hydrogen RD&D in Australia

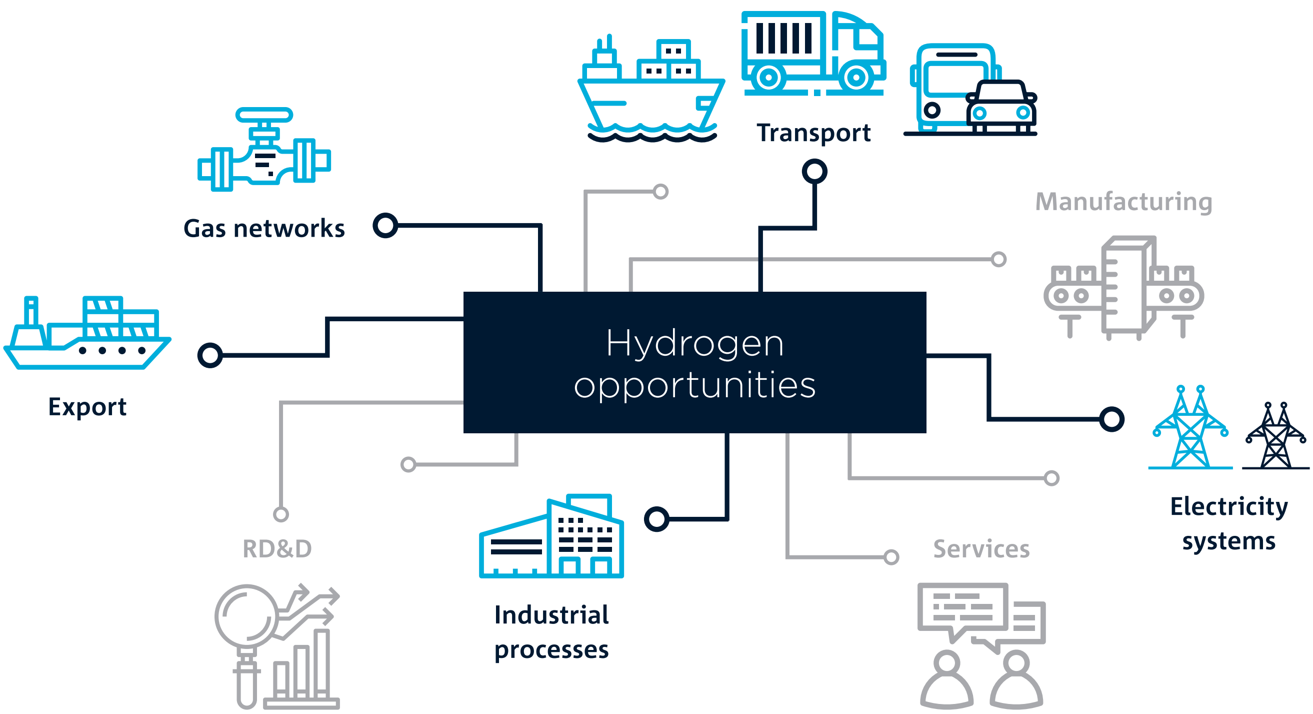
Hydrogen research, development and demonstration (RD&D) in Australia is well-positioned to support hydrogen industry development and contribute to decarbonisation efforts domestically and internationally.

In 2018, CSIRO released the *National Hydrogen Roadmap,*[1] which articulated the opportunity for Australia to support global decarbonisation efforts and build on the nation's resources and skills to develop an economically sustainable domestic and export hydrogen industry. It explored opportunities for hydrogen to become a new Australian export industry and for hydrogen to be used in the gas networks, for transport, electricity systems support and in industrial processes. As the market develops, there will be many more opportunities for Australia beyond those identified, especially for the nation's advanced manufacturing and services sector to support these industries now and into the future (Figure 1).

Further to improvements enabled by factors such as increasing scale, the *Roadmap* identified several ways to improve costs of technologies, including through significant investment in research, development and demonstration (RD&D). This finding aligns with the International Energy *Agency's Future of Hydrogen report,*[2] which also stresses the importance of continued RD&D to improve performance and reduce costs.

Hydrogen RD&D activities span from fundamental technical and non-technical research all the way through to pilot and demonstration projects and can be delivered by researchers, technologists and engineers across both research organisations and industry. RD&D enables the development of state-of-the-art hydrogen production, storage, distribution and utilisation technologies. Developing Australia's hydrogen RD&D community is vital to industry development and growth.

Figure 1: Hydrogen industry opportunities



1 Bruce, S., Temminghoff, M., Hayward, J., Schmidt, E., Munnings, C., Palfreyman, D., Hartley, P. (2018). *National Hydrogen Roadmap*, CSIRO.

2 International Energy Agency (2019). *The Future of Hydrogen: Seizing Today's Opportunities.*

This report

This report builds on the *Roadmap* by identifying opportunities for RD&D to support an Australian hydrogen industry. It was developed in parallel with *Australia's National Hydrogen Strategy* and will support implementation of the Strategy.[3]

Using the widely accepted Technology Readiness Levels (TRL)[4] framework, this report considers the full spectrum of relevant RD&D activities from TRL 1 – 9, recognising that the nature and role of RD&D changes as technology progresses along the TRL spectrum (see Figure 2). This report also considers non-technical or cross-cutting RD&D fields as critical to industry and technology development (e.g. community engagement and environmental assessment). In many cases, these fields are vital to project development and often have unique local parameters that require a research response tailored to Australia's unique circumstances.

To help inform industry, research and government stakeholders, the report is structured around four key messages:

- **Part 1. The value of RD&D and Australia's hydrogen capabilities:** Australia has a well-established RD&D ecosystem and specific hydrogen related capabilities that can be built upon to add meaningful value to the global emerging hydrogen industry. Despite this, there is scope for improvement in the delivery and use of this capability.
- **Part 2. Opportunities for RD&D to support market activation:** Opportunities in hydrogen export, the use of hydrogen in the gas networks, transport, electricity systems and industrial processes all face market activation challenges. While investment and scale-up will address many of these challenges, there are a subset of technical and non-technical challenges that require or could be supported by RD&D.
- **Part 3. Underpinning RD&D across the value chain:** The pursuit of multiple hydrogen opportunities in Australia requires underpinning RD&D activity and capability across the value chain (in production, storage and distribution, utilisation and cross-cutting RD&D fields) and at all stages of technology development. Important considerations for enhancing Australia's hydrogen RD&D ecosystem and shaping Australia's emerging industry include the need for diverse RD&D capability, a focus on cost and efficiency improvements, as well as breakthrough technology areas and the need to develop integrated decision-making support capability.
- **Part 4. Enhancing Australian hydrogen RD&D outcomes:** For the Australian RD&D community to maximise its impact and innovation performance, action must be taken. This includes ongoing development and optimisation of an Australian hydrogen RD&D strategy,

Figure 2: The role of RD&D across all stages of technology development

Concept validation Prototyping and incubation of emerging technology ideas and developing knowledge to support industry development				Development and demonstration De-risking and demonstrating promising technologies opportunities and understanding scale-up requirements			Commercial deployment Delivering continuous improvement in mature technologies and supporting deployment and trouble shooting	
Basic principles observed	Formulation of concept or application	Proof of concept	Validation in lab environment	Validation in relevant environment	Pilot scale validated in relevant environment	Full scale demo. in relevant environment	System complete and qualified and hypothetical commercial proposition	Actual system operated full range conditions (commercial trial, small scale)
TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9

3 Commonwealth of Australia (2019) *Australia's National Hydrogen Strategy.* [Online] Available from: https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf, Accessed: 25/11/2019

4 Australian Renewable Energy Agency (2014). *Technology Readiness Levels for Renewable Energy Sectors.*

encouraging greater RD&D activity in industry scale-up efforts, promoting RD&D connections and contributions to international hydrogen RD&D efforts, and improving hydrogen industry-research collaboration.

These key messages have been developed through a highly collaborative process. Input for this report was sought from all Australian universities, relevant Cooperative Research Centres (CRCs), CSIRO's domain experts and a cross section of industry (see Appendix). In addition to consultations with industry, government and research, a steering committee was convened throughout the project to test findings, approach and key messages.

A collaborative approach

This report is informed by:

Interviews with representatives from 35 industry and government organisations

80+ interviews with researchers from 23 institutions across Australia

Broad literature review

To ensure consistency with the *Roadmap* and *Australia's National Hydrogen Strategy*, when discussing 'hydrogen' this report is implicitly referring to 'clean hydrogen,' defined as being produced using renewable energy or using fossil fuels paired with carbon capture, utilisation and storage (CCUS) to achieve zero-to-low associated carbon emissions. CCUS for this report encompasses methods and technologies to capture CO_2 from fuel combustion, industrial processes or directly from the atmosphere, followed by use of the captured CO_2 to create valuable products, biosequestration or permanent storage through geological storage.

Finally, the analysis informing this report, including detailed technology scans, research institution activity and the methodology for publications and patent analysis can be found in the Hydrogen Research, Development and Demonstration: Technical Repository.[5] Hydrogen RD&D activity is expected to change rapidly over the coming years, as will capabilities that emerge with new projects and research. As such, this Technical Repository has been developed with a view of it becoming a living and digital repository that is maintained overtime.

1.1 Why RD&D

RD&D has an important role to play in enabling the continued development of Australia's hydrogen industry.

Innovation, or the transformation of ideas into solutions, is an important outcome for RD&D. Innovation underpins long run economic progress, as it allows countries to become more competitive, adapt more effectively to change, and improve living standards.[6]

In addition to industrial and technological breakthroughs, process advancements and improvements achieved in the laboratory and through demonstration projects, RD&D can provide models, tools and knowledge which can support individual projects or unlock new opportunities. RD&D can further support technology deployment through research areas such as social and environmental sciences which allow government and communities to assess risks and opportunities in real world settings. This is particularly important given recent findings that Australians view research institutions as the most trusted group to act in the best interest of the public.[7]

5 Charnock, S., Temminghoff, M., Srinivasan, V., Burke, N., Munnings, C., Hartley, P. (2019). *Hydrogen Research, Development and Demonstration: Technical Repository*, CSIRO.

6 OECD (2018). *OECD Science, Technology and Innovation Outlook 2018 – Adapting to Technological and Societal Disruption.*

7 Lambert, V., & Ashworth, P. (2018). *The Australian public's perception of hydrogen for energy,* The University of Queensland, [Online] Available from: https://arena.gov.au/assets/2018/12/the-australian-publics-perception-of-hydrogen-for-energy.pdf

For the emerging hydrogen industry specifically, RD&D can be used to help ensure that Australia becomwwes a key player in the global hydrogen industry· It can do so by:

- **Reducing capital and operating expenses** by achieving improvements in mature and emerging technologies. These improvements and the ability to produce hydrogen at scale are important to support Australia's potential to meet anticipated future demand for hydrogen. For example, Japan has clear long-term hydrogen targets alongside targeted prices (US$3/kg by 2030 and $1.30/kg by 2050).[8] Meeting these long-term targets and satisfying Japan's demand for hydrogen will require significant cost improvements which can be enabled by RD&D.
- **Delivering breakthrough technologies** by identifying and developing opportunities which might offer step-change benefits across the hydrogen value chain. For example, using RD&D to develop opportunities to reduce or eliminate process steps. This could occur within individual parts of the value chain, such as eliminating the need to process a given feedstock for hydrogen production. For example, using low quality or waste water inputs without treatment. Breakthrough technologies could also allow the use of alternative feedstocks, such as biomass or waste streams. Opportunities for step-change could also occur across the value chain, for example, through direct use of carriers like ammonia. While difficult to predict the timeline of such developments, hydrogen RD&D has the potential to support the long-term sustainability of the industry.
- **Helping ensure and demonstrate safety** across production, storage, transport and use of hydrogen. As with many energy carriers, the safe production, storage, distribution and utilisation of hydrogen must be assured. While hydrogen is already used by large industries in Australia and overseas, RD&D can help ensure and demonstrate safety across the value chain as the hydrogen industry evolves and hydrogen is used in new and different applications.
- **Understanding and minimising environmental impacts** of a large-scale hydrogen industry. While hydrogen is inherently a clean energy carrier, understanding and minimisation of the environmental impacts of a large-scale hydrogen industry (e.g. water usage and atmospheric chemistry) will be required.
- **Informing community awareness** through activities such as social research accompanying project demonstrations. Such projects can show Australians how a safe introduction of hydrogen technologies could occur with minimal disruption and bring economic and environmental benefits to the country.
- **Providing clearer direction on demonstration and scale-up requirements** and help de-risk commercial investments. As hydrogen technologies mature and scale up, their ability to integrate into existing systems, such as the electricity grid, and provide multiple "value streams" such as oxygen and heat, need to be understood and optimised for various purposes. This will require a range of modelling activities, research and demonstrations.

Beyond the industry-specific benefits described, hydrogen RD&D could also support the Australian economy by stimulating national and international collaboration and knowledge sharing. This could help support international relationship building, using science (and science networks) to support business-to-business opportunities and as a vehicle for international diplomacy. It could also help to grow technology, manufacturing and service businesses that provide highly competitive solutions to the hydrogen industry and are differentiated using science, technology and innovation.

8 National Hydrogen Strategy Taskforce (2019). *National hydrogen industry – Issues paper series – Developing a hydrogen export industry,* Department of Industry, Innovation and Science, [Online] Available from: https://consult.industry.gov.au/national-hydrogen-strategy-taskforce/national-hydrogen-strategy-issues-papers/

1.2 Australian hydrogen RD&D landscape

Australia has a strong foundation of hydrogen RD&D skills and infrastructure that can support market activation and improve the long-term sustainability of the domestic and international hydrogen industry.

Australia's hydrogen RD&D community is diverse. It includes research institutions as well as local and international industry and technology companies, demonstration projects and hydrogen-specific research facilities across Australia (Figure 3). Together, this community is building local capabilities and demonstrating the use of hydrogen across several applications (Figure 4).

Figure 3: Hydrogen RD&D ecosystem

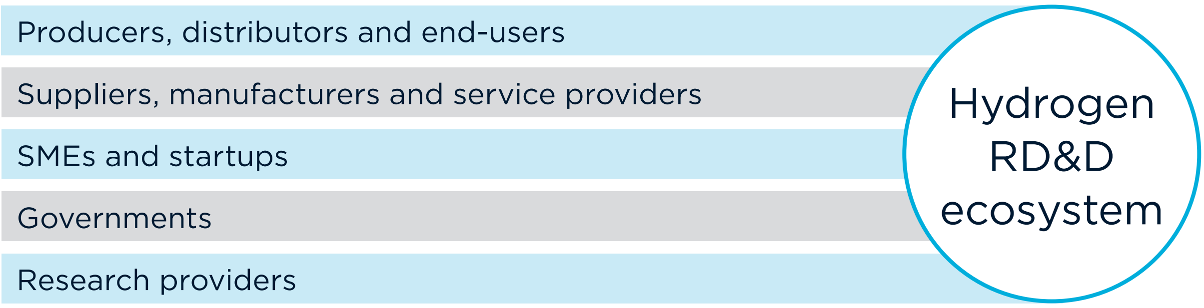
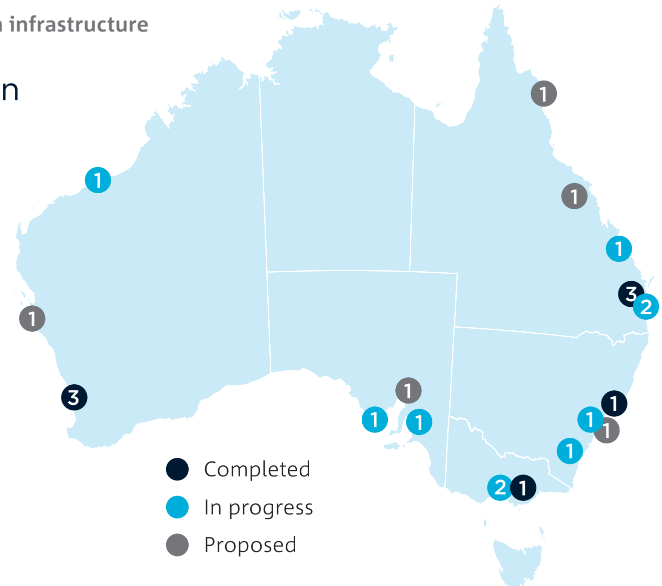


Figure 4: Snapshot of Australian demonstration projects and research infrastructure

23 Hydrogen-specific demonstration projects and research facilities around Australia



WA
- **Hazer Group Pilot Plant** – Hazer Group and MinRes
- **Australian Resources Research Centre** – CSIRO and Curtin Uni
- **Clean Energy Innovation Hub** – ATCO
- **Renewable Hydrogen/Ammonia** – Yara and ENGIE
- **Murchison Renewable Hydrogen Project** – Siemens, Hydrogen Renewables Australia

SA
- **Hydrogen Park SA (HyP SA)** – AGIG and Siemens
- **Port Lincoln Green Hydrogen Plant** – Hydrogen Utility (H2U) and Thyssenkrupp
- **Crystal Brook Energy Park** – Neoen

NSW
- **Fire and Explosion Testing Services (FETS)** – University of Newcastle
- **Jemena's Power to Gas trial** – Jemena
- **ARC Training Centre for The Global Hydrogen Economy** – University of New South Wales

ACT
- **Government Fleet and Refuelling station** – ActewAGL, Neoen, Megawatt Capital, Hyundai

VIC
- **Centre for Hybrid Energy Systems (CHES)** – CSIRO
- **Hydrogen Energy Supply Chain (HESC)** – Kawasaki Heavy Industries (KHI), J-POWER, Iwatani Corporation, Marubeni Corporation, Shell and AGL
- **Toyota Australia Hydrogen Centre** – Toyota Australia

QLD
- **Sir Samuel Griffith Centre renewable hydrogen microgrid** – Griffith University
- **National Hydrogen Materials Reference Facility (NHMRF) –** Griffith University
- **Queensland Centre for Advanced Technology (QCAT)** – CSIRO
- **Renewable Hydrogen Production and Refuelling Project** – BOC
- **Gladstone Advanced Biofuels Pilot Plant** – Northern Oil & AFC Energy
- **Redlands Renewable Hydrogen Plant** – Queensland University of Technology
- **Renewable Hydrogen Microgrid** – Daintree Renewable Energy Inc
- **Renewable Ammonia Plant** – Dyno Nobel

Beyond physical facilities, some institutions are taking a multidisciplinary approach to energy research with an increasing focus on hydrogen. Examples include: The Future Fuels CRC,[9] The Blue Economy CRC,[10] Australian National University's Energy Change Institute,[11] the University of Adelaide's Centre for Energy Technology,[12] University of Technology Sydney's Hydrogen Energy Program,[13] the Melbourne Energy Institute at the University of Melbourne,[14] and the University of Western Australia's Centre for Energy.[15] These knowledge centres aim to incorporate expertise from across one or more universities and industry to develop holistic hydrogen applications.

Finally, while not hydrogen-specific, over the years Australia has also invested in a series of national research facilities that are being used to support research in many fields, including hydrogen energy. For example, ANSTO's Australian Synchrotron[16] and the OPAL research reactor facility[17] were noted in interviews as national facilities that had been used to support characterisation of various materials related to hydrogen energy, such as catalyst and storage materials.

1.3 Achieving impact from hydrogen RD&D

Despite Australia's hydrogen RD&D capability, Australia's performance needs attention

Australia's performance in hydrogen research has room for improvement. One area of consideration is the translation and commercialisation of research and new knowledge to industry. For example, despite a strength in publications, data suggests a weakness in converting research insights into patents and commercial opportunities. This translation issue may relate to the early stage of the domestic hydrogen industry. It may also be partly reflected in the demonstration project map (see Figure 4) as projects listed are generally not related to the next phase of Australian hydrogen technologies.

This innovation performance challenge is not unique to hydrogen and mirrors challenges in Australia's national innovation performance. There are several studies that have explored these national innovation challenges. The most notable is the Innovation and Science Australia 2017 report titled *Australia 2030: Prosperity through Innovation,*[18] which proposed actions to improve Australia's innovation performance.

9 Future Fuels CRC (2019). [Online] Available from: www.futurefuelscrc.com, Accessed: 18/11/2019

10 Blue Economy Cooperative Research Centre (2019). [Online] Available from: blueeconomycrc.com.au, Accessed: 18/11/2019

11 Australian National University (2019). Energy Change Institute [Online] Available from: energy.anu.edu.au, Accessed: 18/11/2019

12 The University of Adelaide (2019). *Centre for Energy Technology* [Online] Available from: www.adelaide.edu.au/cet/ Accessed: 18/11/2019

13 University of Technology Sydney (2019). *Hydrogen Energy Program* [Online] Available from: www.uts.edu.au/about/faculty-engineering-and-information-technology/civil-and-environmental-engineering/cgt-0 Accessed: 18/11/2019

14 University of Melbourne (2019). *Melbourne Energy Institute*, [Online] Available from: energy.unimelb.edu.au Accessed: 18/11/2019

15 University of Western Australia (2010). *Future Energy*, [Online] Available from: www.cfe.uwa.edu.au/research/future-energy Accessed: 18/11/2019

16 ANSTO (2019). *Impact, [Online] Available from:* www.ansto.gov.au/research/facilities/australian-synchrotron/overview Accessed: 18/11/2019

17 ANSTO (2019). *OPAL multi-purpose reactor*, [Online] Available from: www.ansto.gov.au/research/facilities/opal-multi-purpose-reactor Accessed: 18/11/2019

18 Department of Industry, Innovation and Science (2017). *Australia 2030: Prosperity through Innovation*, [Online] Available from: https://www.industry.gov.au/data-and-publications/australia-2030-prosperity-through-innovation

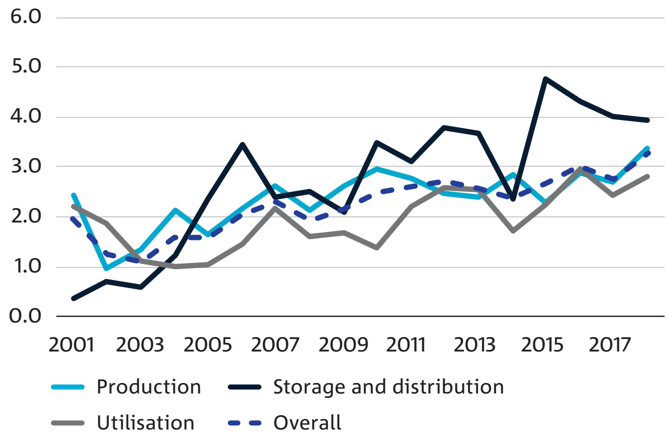
Australian hydrogen publications

Australia is a leading country with respect to global publications in the area of hydrogen research. This is demonstrated by strong performance in publications output, citation impact and international publication collaboration. This places the Australian research community in a strong position internationally.

Global hydrogen research output has increased steadily from ~1,700 publications per year in 2001 to ~11,500 publications per year in 2018. Australian output has also increased, and at a slightly higher rate. Australia's share of hydrogen research grew from 1.5% to 3% over the same period, showing strong growth across the value chain (see Figure 5). Previous studies show that Australia has maintained a strong position in hydrogen research over time, having ranked 7th in hydrogen publications in the 1980s.[19]

The strength in Australia's hydrogen research output is further evidenced by citation impact performance. One approach to assessing this is through Normalised Citation Impact (NCI),[20] which examines how often the publications are cited by other researchers. Figure 6 provides a snapshot of global NCI rankings, which emphasises Australia's strong publications performance across the value chain for the period of 2014-2018.

Figure 5: Australian hydrogen publication output as % of world



Data was drawn from the Web of Science (WoS) from Clarivate and InCites by Clarivate Analytics. The search strategy and keywords used can be found in Hydrogen Research, Development and Demonstration: Technical Repository

Australia's publication collaboration frequency over the previous five years shows a high level of international collaboration with prominent hydrogen-active countries, setting up a strong foundation for collaboration moving forward. The top five countries collaborated with were China, USA, England, Germany and Japan. 62% of Australian publications for the period 2014-2018 involved collaboration with researchers from these countries. Further details of publication collaborations are found in Hydrogen Research, Development and Demonstration: Technical Repository.[21]

Figure 6: Australia's publications ranking based on normalised citation impact (NCI)

Production	Storage	Utilisation	Overall
1st	1st	1st	1st
2nd	2nd	2nd	2nd
3rd	3rd	3rd	3rd

Australia's NCI rank

Data was drawn from the Web of Science (WoS) from Clarivate and InCites by Clarivate Analytics. The search strategy and keywords used can be found in Hydrogen Research, Development and Demonstration: Technical Repository

19 Khalilpour, K., & Pace, R. (2018). *Retrospective and Prospective of the Hydrogen Supply Chain: A Longitudinal Techno-historical Analysis.* Australian National University.

20 Each year, subject area and document type is assigned a baseline, or an expected number of citations for that group. Each publication is then assessed against that baseline (i.e. the number of citations is divided by the expected number of citations). This takes account of any fluctuations in the annual number of publications produced either by the unit of analysis or globally, and removes from comparison any skew based on the age of a publication, its subject area or its type.

21 Charnock, S., Temminghoff, M., Srinivasan, V., Burke, N., Munnings, C., Hartley, P. (2019). *Hydrogen Research, Development and Demonstration: Technical Repository*, CSIRO.

Australia's hydrogen patents

Patent family data[22] can be used to measure innovation and explore how research knowledge is being translated. It is of course not a perfect indicator, as not all innovations result in patents and not all patents result in practical innovations.[23]

To generate insight into Australia's hydrogen IP positioning, a patent landscape search was performed to provide an overview of the technology area's IP history and to compare Australia to other countries over time. The scan returned over 50,000 patent families filed worldwide across the value chain since 1 January 2010.

Excluding Patent Cooperation Treaty applications or European applications which relate to legal jurisdictions rather than physical countries, China, Japan and the US make up the top 3 countries based on first patent family filing, with Australia ranking 10th (see Figure 7). This makes up only 0.5% of the total, which is far below the contribution made in publication metrics as discussed above (3.0%).

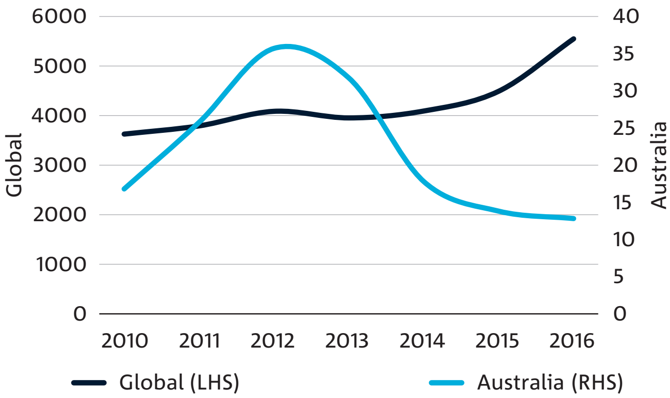
Globally, patent family filing activity for the first patent application in a patent family has increased worldwide over the last 10 years, from 3,650 in 2010 to a peak of 5,610 in 2016 (see Figure 8).

However, the number of those originating in Australia has declined over the same period. Although Australia's research output has increased over the previous years, the conversion of this research into IP has not followed the same trend.

Figure 7: Top 10 hydrogen-related patent family countries of origin

COUNTRY OF ORIGIN	PATENT NUMBER	% OF TOTAL
China	19,259	36.4%
Japan	12,374	23.4%
United States	8,046	15.2%
South Korea	4,220	7.9%
Germany	2,646	5.0%
France	1,343	2.5%
Russia	922	1.7%
United Kingdom	617	1.1%
Taiwan	602	1.1%
Australia	**280**	**0.5%**

Figure 8: Global and Australian patent family filing trend (2010-2016), using the first filing in a patent family[24]



The search strategy and keywords used can be found in Hydrogen Research· Development and Demonstration: Technical Repository

22 Patent families, rather than individual patents, is the metric referred to in the results of the landscape search. A patent family is a group of patents that are related, usually by a priority document or documents, so as to relate to one invention. For example, a patent family may have related patents filed in a number of different countries such as Australia, the United States of America and Japan. Several family members may also be filed in the same country. The number of patent families is typically a better measure for the analytics undertaken as it removes duplicates.

23 Nagaoka, S., Motohashi, K., Goto, A., (2010). *Patent statistics as an innovation indicator*, [Online] Available from: http://dec.ec.unipg.it/~fabrizio.pompei/nagaoka2010.pdf

24 Patent information is not published in databases when a patent is first filed (i.e. at the priority date) and the first publication of information for a patent may not occur for at least 18 months in most cases. Therefore, it is likely that the results for 2017 onwards do not yet include all patent applications. Therefore, results from 2017-2019 have been omitted due to incomplete data at this time.

2 Hydrogen RD&D opportunities to support market activation

Global hydrogen industry developments will address many market activation challenges; however, RD&D is required to overcome current barriers and help stimulate demand.

This report focuses on five hydrogen opportunity areas. However, as the market develops, there will be many more opportunities for Australia beyond those identified here, especially for the nation's advanced manufacturing sector.

Market activation and the realisation of these hydrogen opportunities requires investment from various stakeholder groups (e.g. industry, government and research) so that industry can continue to scale in a coordinated manner.

Global industry development and scale-up will help realise these opportunities. However, many industry challenges require or could be greatly aided by focused RD&D. This chapter identifies market activation challenges and opportunities for the Australian hydrogen RD&D ecosystem. For each opportunity, three short to medium term market activation challenges have been identified (see Figure 9).

Importantly, solving the challenges identified can have a multiplier effect that boosts demand for hydrogen and encourages further hydrogen supply cost reductions through improvements in efficiency and economies of scale. Hydrogen use in industrial processes provides a strong example of this in action given the breadth of industries that already use hydrogen as a feedstock, the number that could use hydrogen and the volume of hydrogen required by these industries to support ongoing operations.

While not exhaustive, these challenges stress the importance of RD&D effort across the value chain (discussed in Part 3). It is important to note that these market activation challenges, and their associated RD&D opportunities, are expected to change over time as the market develops and projects are executed. As such, it is recommended that these market activation challenges are revisited as part of a broader Australian RD&D strategy (discussed in Part 4).

Figure 9: Opportunities and RD&D related challenges

Opportunity	Challenge	Hydrogen production	Storage and distribution	Hydrogen utilisation	Cross-cutting RD&D
Export	Producing low cost hydrogen and hydrogen carriers at scale	✓			✓
	Store and distribute hydrogen economically at scale		✓		✓
	Inform and understand export value chains and market requirements				✓
Gas networks	Develop network and pipeline solutions		✓	✓	✓
	Demonstrate integration of blended and 100% hydrogen in gas networks	✓		✓	✓
	Prepare domestic and commercial appliances for hydrogen gas			✓	✓
Transport	Plan strategic deployment of cost-effective refuelling infrastructure	✓	✓		✓
	Use hydrogen for transport, especially heavy and long-range transport	✓	✓	✓	✓
	Build safety and environmental cases and inform community acceptance				✓
Electricity systems	Understand and manage grid integration of hydrogen technologies	✓	✓	✓	✓
	Integrate hydrogen production and storage solutions in distributed systems	✓	✓	✓	✓
	Develop hydrogen solutions to allow for inter-seasonal variation		✓		✓
Industrial processes	Switch current industrial hydrogen users to clean hydrogen	✓	✓	✓	✓
	Develop use cases to adapt current processes to use hydrogen and its derivatives	✓	✓	✓	✓
	Establish new market opportunities for zero or low emissions hydrogen	✓	✓	✓	✓

■ Hydrogen production ■ Storage and distribution ■ Hydrogen utilisation ■ Cross-cutting RD&D

2.1 Export

2.1.1 Opportunity

Key challenges supported by RD&D

- Produce low cost hydrogen and hydrogen carriers at scale
- Store and distribute hydrogen economically at scale
- Inform and understand export value chains and market requirements

Australia has an extensive history of exporting energy and natural resources to the world, which has created economic benefits and jobs. Global demand for energy in the form of hydrogen is increasing. Long-term import strategies for the element have been set by Asian neighbours like South Korea and Japan and numerous reports have outlined Australia's great potential to produce and export hydrogen due to its geography and natural resources, highlighting a large opportunity for Australia. Attempts to quantify the opportunity have been undertaken by many organisations:

- The Economic Research Institute for ASEAN has forecasted that Australia could supply 42% of East Asia's hydrogen demand by 2040[25]
- The IEA calculates that given its natural resources, Australia could produce nearly 100 million tonnes of oil equivalent of hydrogen[26]
- In a report commissioned by ARENA, ACIL Allen valued exports in 2040 ranging from $2.6 billion to $13.4 billion[27]

Beyond the value of hydrogen carriers for storage and distribution, is the potential for direct use of carriers to support broader decarbonisation efforts. An example of this can be seen through the direct use of ammonia, which is being considered as a fuel in the maritime industry. The direct use of carriers is discussed further in Part 3.3.

2.1.2 Challenges and RD&D opportunities

The National Hydrogen Strategy Issues Papers highlighted several actions required to unlock an export industry that include production at scale, country-to-country agreements, international engagement, securing offtake agreements and overcoming technical barriers.[28] Outlined below are those where RD&D can play a role.

CHALLENGE	PRODUCE LOW COST HYDROGEN AND HYDROGEN CARRIERS AT SCALE	
Context	Countries that have declared hydrogen import targets have also outlined the hydrogen price they expect to pay. These prices will require significant reductions in hydrogen costs over the coming decades as well as highly scaled production plants. The cost reductions and the build-up of export scale production facilities will be greatly assisted by RD&D.	
RD&D opportunities	**Production (Part 3.1)**	• Develop low cost and efficient hydrogen production processes and enhance safety and sustainability at a large scale. This includes developing emerging low-emissions production technologies, some of which may make use of different feedstocks. • Conduct medium to large scale demonstrations to gather system learnings and improve system integration.
	Cross-cutting RD&D (Part 3.4)	• Conduct modelling to inform production technology choice and optimise the location of production facilities.

25 Kimura, S., & Li, Y. (2018). *Demand and Supply Potential of Hydrogen Energy in East Asia*, Economic Research Institute for ASEAN and East Asia (ERIA).

26 International Energy Agency (2018). *World energy outlook 2018*, OECD/IEA.

27 ACIL Allen Consulting for ARENA (2018). *Opportunities for Australia from hydrogen exports.*

28 National Hydrogen Strategy Taskforce (2019). *National hydrogen industry – Issues paper series – Developing a hydrogen export industry*, Department of Industry, Innovation and Science, [Online] Available from: https://consult.industry.gov.au/national-hydrogen-strategy-taskforce/national-hydrogen-strategy-issues-papers/

CHALLENGE	STORE AND DISTRIBUTE HYDROGEN ECONOMICALLY AT SCALE	
Context	Hydrogen has a very low volumetric density as an unpressurised gas, making it uneconomical to transport in this way. To improve the economics of transporting hydrogen, different technologies can be used to change the state and pressure in which the hydrogen is stored.	
RD&D opportunities	**Storage and distribution (Part 3.2)**	• Develop, test and demonstrate of various hydrogen storage systems and carrier ships for export. This may also include considering how intermittent renewables could be coupled with non-intermittent carrier processes. • Advance alternative systems for hydrogen storage through alternative materials or processes for lowering costs, improving volumetric and gravimetric storage capacity and roundtrip energy efficiency. • Explore effective handling and regeneration of carriers and materials (subject to storage type). • Develop, demonstrate and optimise hydrogen storage and transport mechanisms to deliver hydrogen from production facilities to loading ports.
	Cross-cutting RD&D (Part 3.4)	• Conduct techno-economic modelling to optimise storage and distribution technology choices. For example, considering customer preferences for compressed hydrogen, cryogenic hydrogen, or chemical hydrogen carriers based upon factors such as safety, costs, reusability, handling requirements, and shipping requirements.

CHALLENGE	INFORM AND UNDERSTAND EXPORT VALUE CHAINS AND MARKET REQUIREMENTS	
Context	Like all large-scale development, it is important to analyse and manage risks to stakeholders and the environment to earn a social licence to operate. For the emerging hydrogen industry this requires a greater understanding of export value chains and the drivers and goals of key stakeholders in target markets.	
RD&D opportunities	**Cross-cutting RD&D (Part 3.4)**	• Conduct global value chain and market analysis to understand short- and long-term Government and industry requirements. Beyond economic or financial goals, it is important to understand requirements related to hydrogen infrastructure, scale-up, terms of trade, sovereign risk and provenance, environment (such as carbon risk drivers), health and safety and community engagement. • Develop clear, internationally accepted classifications and processes to account for clean hydrogen provenance to guarantee origin. • Develop hydrogen industry-specific methods of environmental accounting. • Design and deploy community engagement strategies (drawing on past examples) to support large export projects - e.g. some concern has been expressed that Australia would be exporting its water, which is seen as a limited and precious resource.[29] • Understand and support the development (if required) of port safety rules and regulations; including emergency procedures and clean up, depending on distribution method. • Conduct environmental assessments and analysis for projects. For example, environmental considerations related to the integration of hydrogen production with CCUS or other carbon sequestration methods (where required).

29 Lambert, V., & Ashworth, P. (2018). *The Australian public's perception of hydrogen for energy*, The University of Queensland, [Online] Available from: https://arena.gov.au/assets/2018/12/the-australian-publics-perception-of-hydrogen-for-energy.pdf

2.2 Gas networks

2.2.1 Opportunity

Key challenges supported by RD&D

- Develop network and pipeline solutions
- Demonstrate integration of blended and 100% hydrogen in gas networks
- Prepare domestic and commercial appliances for hydrogen gas

Introducing hydrogen into the existing natural gas networks is currently underway with pilots across the country already announced, creating many opportunities for Australia.

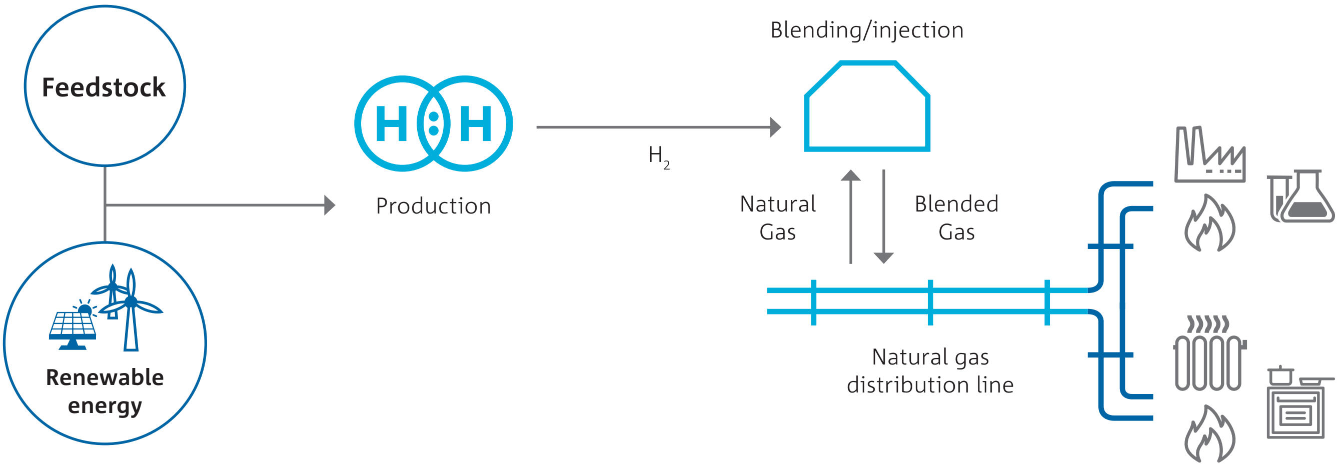
From a heating perspective, the blending or use of 100% hydrogen in gas networks presents an opportunity to decarbonise the existing gas network by providing domestic, commercial and industrial customers with a lower carbon gas for heating and energy. Annual emissions for the year to December 2018 show that energy from the direct combustion of fuels accounts for 19.1% of Australia's emissions, making it the 2nd largest sector as well as the fastest growing.[30] This gas can also be utilised by gas peaking plants, to aid in decarbonising electricity generation.

Further, parts of the existing gas distribution infrastructure can be utilised as a pure hydrogen distribution network, providing a potentially more cost-effective alternative to road distribution. Finally, with domestic natural gas prices high (highest in eastern states at $8-10/GJ),[31] and reserves locked up in long-term contracts, blended gas could reduce the pressure on natural gas. In fact, the use of 100% hydrogen gas streams could eventually replace the domestic reliance on natural gas altogether.

2.2.2 Challenges and RD&D opportunities

The National Hydrogen Strategy Issues Papers highlighted several challenges that need to be overcome to facilitate the introduction of hydrogen into the gas network, including assessing the suitability of existing gas infrastructure and appliances, achieving customer acceptance and ensuring industrial customers get the correct gas combination for their processes.[32] Outlined below are those where RD&D can play a role.

Figure 10: Hydrogen blending and injection into gas networks



30 Commonwealth of Australia (2019). *Quarterly Update of Australia's National Greenhouse Gas Inventory: December 2018. Department of the Environment and Energy*, [Online] Available from: https://www.environment.gov.au/system/files/resources/408fcc37-dcfd-4ab8-a4f9-facc6bd98ea6/files/nggi-quarterly-update-dec-2018.pdf

31 Bruce, S., Temminghoff, M., Hayward, J., Schmidt, E., Munnings, C., Palfreyman, D., Hartley, P. (2018). *National Hydrogen Roadmap*, CSIRO.

32 National Hydrogen Strategy Taskforce (2019). *National hydrogen industry – Issues paper series – Hydrogen in the gas network*, Department of Industry, Innovation and Science, [Online] Available from: https://consult.industry.gov.au/national-hydrogen-strategy-taskforce/national-hydrogen-strategy-issues-papers/supporting_documents/NationalHydrogenStrategyIssue6HydrogeninGasNetwork.pdf

CHALLENGE	DEVELOP NETWORK AND PIPELINE SOLUTIONS	
Context	Hydrogen has different characteristics compared to natural gas which means that it interacts with pipeline materials differently. When the gases are mixed or if hydrogen is transmitted as the sole gas, the effects on pipeline infrastructure need to be considered to minimise leakage, ensuring safe transmission and reduced economic impact of losses.	
RD&D opportunities	**Storage and distribution (Part 3.2)**	• Understand network and pipeline effects from hydrogen and hydrogen mixes on distribution and transmission pipelines to support site-by-site injection trials and long-term use. This includes understanding steel pipeline and component part material performance, how pipeline characteristics vary by location and geography, and any associated replacement or augmentation considerations due to embrittlement or cracking risks.[33] • Develop methods and identify suitable (or novel) materials and components to support network operations. For example, more efficient seals and pipe joints to minimise leakage or lower costs. This may come through scale-up and RD&D in manufacturing methods.
	Utilisation (Part 3.3)	• Test or develop gas meters and sensors to accurately measure hydrogen flow rates and volumes and support different concentrations of hydrogen blending and injection (including accounting for distribution pressures and natural gas requirements to balance differences in heating values). These sensors could also be leveraged to provide data on network health and maintenance. • Test or further develop specialised technologies and sensors (where needed) for injection and separation. For example, technologies to support the separation of hydrogen from blended gas for different residential, commercial and industrial customers.
	Cross-cutting RD&D (Part 3.4)	• Conduct modelling and analysis to articulate the value of sector coupling such as between the electricity and gas sectors. This may include analysis on regulations related to gas and electricity networks. • Conduct modelling to map locations for where 100% hydrogen would be more economic than electrification. This includes considering long-term upgrades to network infrastructure.

33 National Hydrogen Strategy Taskforce (2019). *National hydrogen industry – Issues paper series – Hydrogen in the gas network*, Department of Industry, Innovation and Science, [Online] Available from: https://consult.industry.gov.au/national-hydrogen-strategy-taskforce/national-hydrogen-strategy-issues-papers/supporting_documents/NationalHydrogenStrategyIssue6HydrogeninGasNetwork.pdf

CHALLENGE	DEMONSTRATE INTEGRATION OF BLENDED AND 100% HYDROGEN IN GAS NETWORKS	
Context	The ability to supply hydrogen safely and cost-effectively at scale will be required to support uptake of 100% hydrogen or hydrogen blends. As with conventionally used natural gas, hydrogen is flammable and poses a safety risk due to potential ignition and flame speed and visibility. Safety is the main concern for consumers in the domestic context and without social acceptance, the industry will not develop in an accelerated manner. Furthermore, as implementation of higher hydrogen blends across larger areas increases, hydrogen must be produced at a large enough volume to meet demand. In order to gain uptake by industry and acceptance from the community, the ability to supply hydrogen safely and cost-effectively at scale will be required.	
RD&D opportunities	**Production (Part 3.1)**	• Develop cost-effective large- and small-scale hydrogen production technologies to support distribution and transmission network trials and larger scale roll-outs.
	Utilisation (Part 3.3)	• Test or develop leak detection and safety shut-off devices capable of proactively detecting and responding to a 100% hydrogen or blended gas leakage risk – for use in different industrial and customer environments (where needed). • Develop low cost and efficient hydrogen production processes and enhance safety and sustainability at a large scale. • Conduct medium to large scale demonstrations of 100% hydrogen and hydrogen blends in domestic, commercial and industrial customer environments to build confidence, gather technical and system learnings and improve system integration.
	Cross-cutting RD&D (Part 3.4)	• Inform regulatory and standards modifications regarding the use of materials for hydrogen pipelines, appliances, the use of odorants, the separating of hydrogen for end-users, and others. • Support assessments and analysis to help demonstrate the safe use of hydrogen in gas networks. • Engage with communities to understand and address safety concerns and build consumer confidence regarding use of 100% or blended hydrogen gas streams. • Conduct environmental assessments and analysis for projects. For example, environmental considerations related to the integration of hydrogen production with CCUS or other carbon sequestration methods (where required).

CHALLENGE	PREPARE DOMESTIC AND COMMERCIAL APPLIANCES FOR HYDROGEN GAS	
Context	Addition of hydrogen to natural gas changes its characteristics. This has downstream effects on appliances given the different burning behaviour. This change was similarly experienced in the change from town gas to natural gas. The effect that new gas compositions or 100% hydrogen will have on domestic and commercial customers needs to be clear.	
RD&D opportunities	**Utilisation (Part 3.3)**	• Develop appliance components fit to handle higher hydrogen content gas. This includes appliances that can handle natural gas, hydrogen blends and 100% hydrogen. • Develop and test multi-fuel and multi-blend appliances. • Develop technologies to separate hydrogen from gas compositions for low electricity or heat requirements as well as customers who require methane.
	Cross-cutting RD&D (Part 3.4)	• Model the phased rollout of hydrogen blending ‘zones’ based on appliance compatibility and requirements. • Conduct analysis and mapping of different appliances (e.g. makes, model, manufactures) in a national database with location. • Inform industry procedures to support the testing of residential devices for suitability to increasing hydrogen blends or 100% hydrogen gas streams.

2.3 Transport

2.3.1 Opportunity

Key challenges supported by RD&D

- Plan strategic deployment of cost-effective refuelling infrastructure
- Use hydrogen for transport, especially heavy and long-range transport
- Build safety and environmental cases and inform community acceptance

The transport sector is Australia's third largest source of greenhouse gas emissions (18.9%) and has so far received little focus for emission reduction.[34] There is significant potential for hydrogen and its carriers to be adopted as a low to zero-emission transport fuel across Australia.

The versatility of hydrogen and its carriers as an energy source, coupled with its high energy density, lends itself to be adopted in numerous mobility types to aid in decarbonising the sector (Figure 11). For example, hydrogen and its carriers can be fed into fuel cells to power electric drive trains or combusted to drive turbines and engines without producing CO_2 emissions.

Additionally, it would provide an opportunity to improve liquid fuel security; Australia still does not meet its domestic fuel reserve targets set by the IEA and about 90% of fuels used are derived from oil sourced from overseas.[35] Domestically produced hydrogen fuels could help mitigate the risk of fuel disruptions.

2.3.2 Challenges and RD&D opportunities

The National Hydrogen Strategy Issues Papers highlighted several challenges that need to be overcome to facilitate the use of hydrogen as a fuel. This includes vehicle supply and capital costs, vehicle regulation, fuel price and supply as well as refuelling infrastructure.[36]

Figure 11: Potential hydrogen and hydrogen carrier transport and mobility applications

Land	Water	Air
• E-bikes	• Submersible drones	• Unmanned aerial vehicles (UAVs)
• Scooters and motorcycles	• Ferries	• Air taxis
• Materials handling	• Submarines	• Helicopters
• Passenger vehicles	• Cruise ships	• Aeroplanes
• Buses	• Cargo ships	• Spacecraft
• Long haul trucks		
• Heavy haul trucks		
• Trains		
• Specialist mining vehicles		

34 Commonwealth of Australia (2019). *Quarterly Update of Australia's National Greenhouse Gas Inventory: December 2018.* Department of the Environment and Energy, [Online] Available from: https://www.environment.gov.au/system/files/resources/408fcc37-dcfd-4ab8-a4f9-facc6bd98ea6/files/nggi-quarterly-update-dec-2018.pdf

35 Commonwealth of Australia (2019). *Liquid Fuel Security Review: Interim Report*, Department of the Environment and Energy, [Online] Available from: https://www.environment.gov.au/system/files/consultations/7cf6f8e2-fef0-479e-b2dd-3c1d87efb637/files/liquid-fuel-security-review-interim-report.pdf

36 National Hydrogen Strategy Taskforce (2019). *National hydrogen industry – Issues paper series – Hydrogen for transport*, Department of Industry, Innovation and Science, [Online] Available from: https://consult.industry.gov.au/national-hydrogen-strategy-taskforce/national-hydrogen-strategy-issues-papers/supporting_documents/NationalHydrogenStrategyIssue8HydrogenforTransport.pdf

CHALLENGE	PLAN STRATEGIC DEPLOYMENT OF COST-EFFECTIVE REFUELLING INFRASTRUCTURE	
Context	While the expected retail costs of hydrogen are currently unknown, initial information suggests that prices of hydrogen will be comparable to that of petroleum currently used in internal combustion engine vehicles.[37] However, minimal infrastructure exists for refuelling hydrogen vehicles, presenting a barrier to public uptake. While costs related to refuelling stations are coming down through economies of scale, deployment can be optimised with a strategic approach that leverages refuelling infrastructure for multiple uses. For example, the infrastructure could be used to support vehicles, buses, forklifts, garbage trucks and trains. Such an approach should also consider effective hydrogen production and storage and distribution solutions to ensure that hydrogen is always available across the refuelling station network.	
RD&D opportunities	**Production (Part 3.1)**	• For centralised contexts, identify and tailor large-scale hydrogen and hydrogen carrier production technologies to support demand and offtake to refuelling stations. • For distributed contexts, identify and tailor small-scale hydrogen production technologies to support on-site hydrogen generation.
	Storage and distribution (Part 3.2)	• Improve hydrogen and hydrogen carrier storage systems for high volumetric density on-site storage. • If pipelines are used for distribution, test pipeline compatibility with higher hydrogen blends (up to 100% hydrogen gas streams), and design effective gas separation technologies. • Reduce refuelling station capital costs through new component designs and more efficient manufacturing methods.
	Cross-cutting RD&D (Part 3.4)	• Conduct economic and technoeconomic modelling to support selection of refuelling station locations and phased rollout of subsequent networks. This includes considering multi-use opportunities across a range of stakeholders. For example, exploring opportunities for refuelling infrastructure to support local businesses and communities as well as longer-term Federal, State and Local government objectives. • Conduct economic and technoeconomic modelling to optimise hydrogen production (centralised or distributed) and storage and distribution (pipeline, truck with on-site storage) pathways for a given location • Conduct safety assessments and integration modelling for safe and efficient deployment in dense urban and suburban contexts.

CHALLENGE	USE HYDROGEN FOR TRANSPORT, ESPECIALLY HEAVY AND LONG-RANGE TRANSPORT
Context	A challenge relate to the rollout of FCEVs is the misalignment between hydrogen supply and demand (often described by many stakeholders as a chicken and egg situation). To address this challenge and support broader uptake, market activation can be aided by investment in multiple types of transport applications. For example, while there are existing hydrogen buses, trains and forklifts, RD&D can be used to explore and develop technologies and infrastructure to support heavy vehicle and long-range transport applications that have requirements beyond current FCEV technology. In heavy vehicles, Australia uses unique long-haul trucks and mining vehicles which carry large loads, travel significant distances and, in the case of mining, need to operate continuously (which necessitates vast on-board storage requirements). Long-range transport applications, such as marine transport, plays an important role in Australia's export industries and can promote larger scale investments in hydrogen and hydrogen carrier production and refuelling infrastructure.

37 National Hydrogen Strategy Taskforce (2019). *National hydrogen industry – Issues paper series – Hydrogen for transport*, Department of Industry, Innovation and Science, [Online] Available from: https://consult.industry.gov.au/national-hydrogen-strategy-taskforce/national-hydrogen-strategy-issues-papers/supporting_documents/NationalHydrogenStrategyIssue8HydrogenforTransport.pdf

CHALLENGE	USE HYDROGEN FOR TRANSPORT, ESPECIALLY HEAVY AND LONG-RANGE TRANSPORT	
RD&D opportunities	**Production (Part 3.1)**	• Develop low-cost on-site hydrogen production technologies, integrated with energy supply and refuelling systems.
	Storage and distribution (Part 3.2)	• Develop and optimise refuelling infrastructure to increase refuelling rates by an order of magnitude to support fast refuelling for heavy and long-range transport. • Undertake life-cycle and efficiency analysis for hydrogen and hydrogen carrier storage systems. • Develop larger capacity on-site storage systems, integrated with supply and refuelling infrastructure. • Maximise hydrogen density of storage systems or engineer larger storage vessels for on-board vehicle storage.
	Utilisation (Part 3.3)	• Test and demonstrate hydrogen and its carriers for use in heavy vehicles and in long-range transport, where durability and lifetime are critical characteristics. This may require hydrogen propulsion research or internal combustion engine development to support the burning of blends of hydrogen or 100% hydrogen. • Develop or modify heavy vehicles and marine transport to use hydrogen and its carriers as an energy source. This may require the development or modification of new engines and storage tanks or integration and testing of systems. • Optimise system integration and synergies of fuel cells and batteries to power electric drivetrains.
	Cross-cutting RD&D (Part 3.4)	• Model the supply chain to determine ideal zones, corridors or back-to-base networks for initial rollout. For long-range transport (e.g. maritime and commercial aviation), this will require broader value chain analysis. • Conduct modelling to understand potential impacts of policies such as subsidies to support hydrogen heavy vehicle and long-range transport uptake. • Support the development of policy, regulations or certifications for different hydrogen transport use-cases (where required).

CHALLENGE	BUILD SAFETY AND ENVIRONMENTAL CASES AND INFORM COMMUNITY ACCEPTANCE	
Context	While public concern exists regarding the safety risks that hydrogen vehicles and refuelling stations pose, there is general support for the introduction of hydrogen fuel cell buses and long-haul trucks.[38] The safety challenges of hydrogen itself will also need to be addressed. The greatest (and highest profile) risk is potential ignition of a hydrogen leakage at a station or vehicle.[39] As hydrogen-related incidents have occurred, safe demonstrations and public education are needed.	
RD&D opportunities	**Cross-cutting RD&D (Part 3.4)**	• Demonstrate hydrogen safety: Rollout of hydrogen-powered public transport has been suggested as a strong option for building initial public familiarity with and support for FCEVs.[40] • Develop more sensitive hydrogen sensors for leak detection • Raise public awareness and community acceptance through communication of zero emissions transport options, including but not limited to fuel cell technology, and their potential role in the decarbonisation of transport. • Educate relevant professionals about safety standards for hydrogen refuelling stations, and safe response to hydrogen-related incidents.[41] • Conduct modelling of hydrogen leakage and ignition risks, and flame testing.

38 Lambert, V., & Ashworth, P. (2018). The Australian public's perception of hydrogen for energy, The University of Queensland, [Online] Available from: https://arena.gov.au/assets/2018/12/the-australian-publics-perception-of-hydrogen-for-energy.pdf

39 Dagdougui, H., Sacile, R., Bersani, C., Ouammi, A. (2018). *Hydrogen Infrastructure for Energy Applications*. Academic Press.

40 Lambert, V., & Ashworth, P. (2018). *The Australian public's perception of hydrogen for energy*, The University of Queensland, [Online] Available from: https://arena.gov.au/assets/2018/12/the-australian-publics-perception-of-hydrogen-for-energy.pdf

41 U.S. Drive (2017). *Hydrogen Delivery Technical Team Roadmap*, [Online] Available from: https://www.energy.gov/sites/prod/files/2017/08/f36/hdtt_roadmap_July2017.pdf

2.4 Electricity systems

2.4.1 Opportunity

Key challenges supported by RD&D

- Understand and manage grid integration of hydrogen technologies
- Integrate hydrogen production and storage solutions in distributed systems
- Develop hydrogen solutions to allow for inter-seasonal variation

The prospect of the deployment of large-scale distributed hydrogen production has many positive implications for electricity systems, particularly the electricity grid, as more renewables are introduced.

With electrolysis, intermittent excess renewable energy can be used to produce hydrogen, a renewable fuel with benefits within and beyond electricity systems (see Figure 12). Large-scale electrolysis can balance production and consumption in electricity markets. It can also be used to support short term network stability by providing frequency control ancillary services (FCAS). Importantly, hydrogen can also be 'exported' from electricity systems and markets for use as a fuel in industry and transport. As distinct from storage, this permanently removes (and captures value from) renewable energy whose generation might have otherwise been curtailed.

Furthermore, as regional areas move towards renewable and storage options for energy generation, the development of distributed hydrogen systems such as hydrogen remote area power systems (RAPS) provides an opportunity for self-sufficient long-term energy storage and back up generation in locations where there is a dependence on diesel shipments. These areas would also

Figure 12: Variable renewable energy scenarios with electrolyser balancing

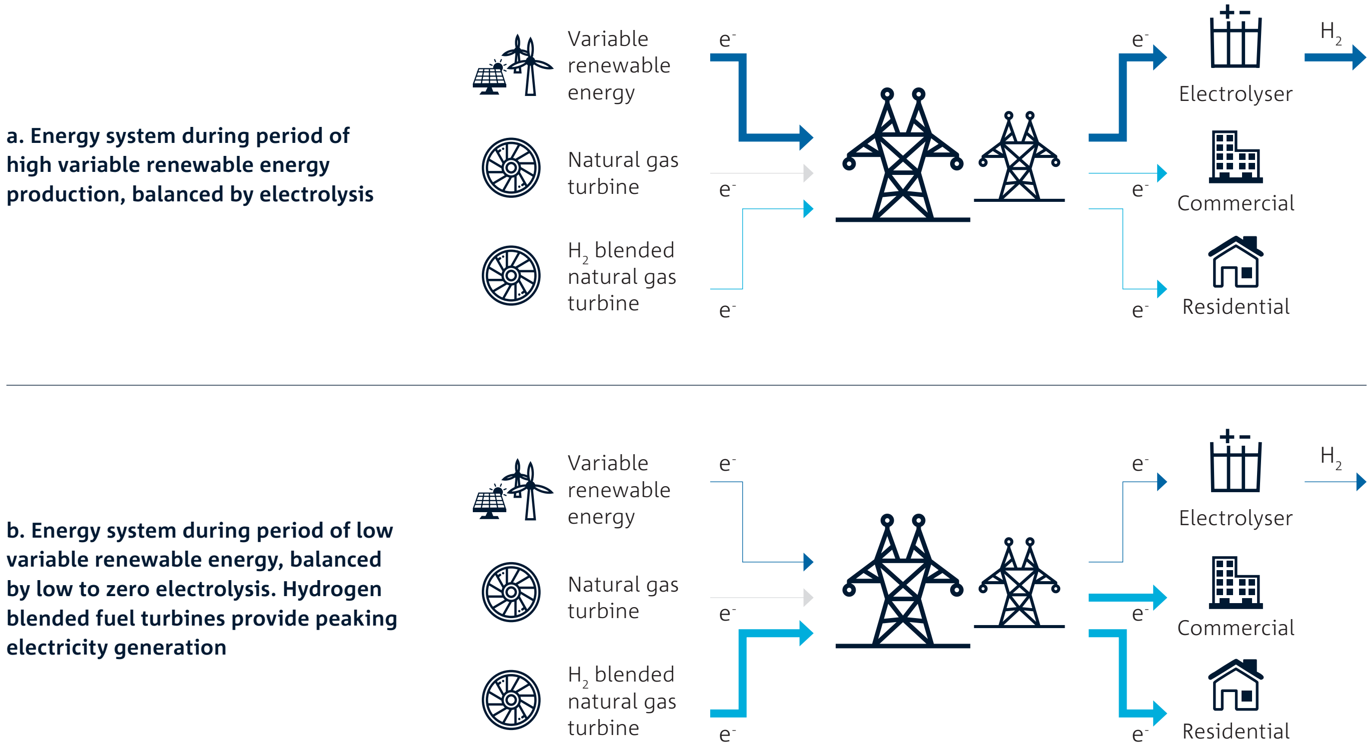


Image developed with Hydricity Systems

benefit from air quality improvements associated with not burning diesel and the increased fuel security from not having to rely on regular shipments of diesel, which could be interrupted.

Importantly, hydrogen use in both centralised and distributed electricity systems will depend on market economics, frameworks and incentives.

2.4.2 Challenges and RD&D opportunities

The National Hydrogen Strategy Issues Papers highlighted several challenges that need to be overcome to use hydrogen technologies to support electricity systems, including market and regulatory reforms and asset placement optimisation.[42] Outlined below are those where RD&D can play a role.

CHALLENGE	UNDERSTAND AND MANAGE GRID INTEGRATION OF HYDROGEN TECHNOLOGIES	
Context	Hydrogen production methods that require a grid connection have few demonstrations. Increasing this will provide learnings on how to optimise plugging these technologies into the grid to lower risks, enhance benefits and take advantage of opportunities.	
RD&D opportunities	**Production (Part 3.1)**	• Develop or improve upon both centralised and decentralised production technologies for different use cases: small-scale or distributed systems capable of rapid ramp up and down; and large-scale or centralised systems capable of rapid ramping up and down to accommodate for renewable energy supply variability.
	Storage and distribution (Part 3.2)	• Develop stationary hydrogen storage technologies to act as a buffer for electricity grid stabilisation.
	Utilisation (Part 3.3)	• Support the continued development of existing fuel cell and turbine technologies to better suit grid conditions and requirements. • Support research into conversion of internal combustion engines into using hydrogen as a fuel (e.g. in the form of ammonia). • Develop solutions that optimise the integration of production, storage and utilisation technologies with the grid in optimal ways.
	Cross-cutting RD&D (Part 3.4)	• Conduct modelling to better understand hydrogen production cost structure and balance of plant requirements at large scale. • Conduct modelling and analysis to inform and optimise production, storage, distribution and utilisation technology and integration choices. Considerations include asset placement, if production is on-grid or off-grid or if hydrogen production should be continuous or not. Ultimately these considerations and the analysis conducted can and should be founded on system designs and basic market economics. • Support the development of legal and regulatory frameworks for the integration of hydrogen technologies into the grid.

42 National Hydrogen Strategy Taskforce (2019). *National hydrogen industry – Issues paper series – Hydrogen to support electricity systems*, Department of Industry, Innovation and Science, [Online] Available from: https://consult.industry.gov.au/national-hydrogen-strategy-taskforce/national-hydrogen-strategy-issues-papers/supporting_documents/NationalHydrogenStrategyIssue7HydrogentoSupportElectricitySystems.pdf

CHALLENGE	INTEGRATE HYDROGEN PRODUCTION AND STORAGE SOLUTIONS IN DISTRIBUTED SYSTEMS	
Context	The use of hydrogen in distributed systems such as remote area power systems (RAPS) or micro-grids could be used to support remote communities and industries. They can be used to reduce reliance on diesel-based generators. For example, diesel-based systems can have a high cost due to the need to import fuel via truck to remote communities and industries and can have an adverse impact on air quality. A hydrogen-based RAPS system could be more cost effective at scale and allow for longer storage periods in harsher operating conditions.[43] In the case of some micro-grids, hydrogen can be used to provide backup power when outages or disruptions to the grid occur. There are several companies working on distributed systems. However, further demonstration projects would be required to optimise these systems depending on the energy and load profiles of remote communities and industries. This may include optimisation of hybrid systems which include batteries. The scale of these system will have large ramifications on technology selection, requiring serious consideration.	
RD&D opportunities	**Production (Part 3.1)**	• Develop low cost small- and large-scale hydrogen production technologies to fulfil requirements of use, e.g. remote community or industry use.
	Storage and distribution (Part 3.2)	• Develop low cost stationary hydrogen storage technologies to support long-term or seasonal storage requirements.
	Utilisation (Part 3.3)	• Develop low cost fuel cells and turbines to support distributed applications. Look at alternative solutions such as converting diesel generators/internal combustion engines to using hydrogen (as ammonia) for fuel.
	Cross-cutting RD&D (Part 3.4)	• Conduct modelling and feasibility studies to understand and optimise project economics and technology integration related to distributed systems. This would need to be conducted on a project by project basis, considering load profiles, other existing or planned renewable and storage infrastructure, distance considerations for fuel supply and renewable penetration (e.g. compared with battery systems). • Model cost-effective methods to store hydrogen seasonally to accommodate seasonal energy demand fluctuations. • Engage with industry and communities to understand concerns (such as water related concerns if on-site electrolysis is being used) and develop communication plans and strategies to manage any issues.

CHALLENGE	DEVELOP HYDROGEN SOLUTIONS TO ALLOW FOR INTER-SEASONAL VARIATION	
Context	While electricity grid firming is a valuable opportunity for hydrogen systems, being able to provide both electricity grid stability (i.e. seconds to hourly storage) and grid reliability (i.e. seasonal storage) services, there remain challenges in developing large scale hydrogen storage solutions that can accommodate significant changes in inter-seasonal energy demand.	
RD&D opportunities	**Storage and distribution (Part 3.2)**	• Identify suitably located salt caverns or depleted gas reservoirs that have the potential to be repurposed for large scale hydrogen storage. • Develop methodology for assessing sites. • Conduct feasibility studies using salt caverns or depleted gas reservoirs for long term, large scale hydrogen storage.[44] • Overcome challenges associated with impurity gases already contained within a gas field. • Identify the presence of any microorganisms in pilot sites and analyse any adverse effect on hydrogen purity and losses; e.g. sulphate reducing bacteria could contaminate the gas with H_2S.[45] • Develop simulation technology for subsurface mixtures of hydrogen and other gases.
	Cross-cutting RD&D (Part 3.4)	• Develop clear information on the unique impacts that large scale storage may have if developed on Indigenous lands and engage with Traditional Owners to build appropriate guiding principles for access and benefit sharing agreements.

43 Bruce, S., Temminghoff, M., Hayward, J., Schmidt, E., Munnings, C., Palfreyman, D., Hartley, P. (2018). *National Hydrogen Roadmap*, CSIRO.

44 Bruce, S., Temminghoff, M., Hayward, J., Schmidt, E., Munnings, C., Palfreyman, D., Hartley, P. (2018). *National Hydrogen Roadmap*, CSIRO.

45 Amid, A., Mignard, D. and Wilkinson, M. (2016). *Seasonal storage of hydrogen in a depleted natural gas reservoir*, International Journal of Hydrogen Energy, Volume 41, Issue 12, Pages 5549-5558.

2.5 Industrial processes

2.5.1 Opportunity

Key challenges supported by RD&D

- Switch current industrial users of hydrogen to zero or low emissions hydrogen
- Develop use cases to adapt current processes to use hydrogen and its derivatives
- Establish new market opportunities for zero or low emissions hydrogen

Hydrogen is already used as a common feedstock in several industries including glass manufacturing, food production, petrochemicals (hydro-treating or hydrocracking), biofuels, methanol synthesis and ammonia synthesis. Most of this hydrogen is currently derived from fossil fuels without the use of CCUS. By shifting to zero or low emissions hydrogen, these industries have an opportunity to decarbonise.

The use of hydrogen in industrial processes has also been identified as an opportunity to reduce emissions in harder-to-abate sectors such as metals processing. While hydrogen is already used to treat some metals (such as nickel), there is an opportunity for further decarbonisation in the iron and steel making process. While other pathways exist to reduce energy and emissions, like the replacement or blending of coking coal with charcoal from biomass, new steelmaking processes using clean hydrogen could enable a 98% reduction in emissions compared with the blast furnace-basic oxygen furnace route.[46] An example can be seen through the HYBRIT project in Sweden by SSAB, LKAB and Vattenfall who are planning to convert their steelmaking process from blast furnace to using hydrogen for direct reduction of iron (DRI), with the first commercial plant expected to be operational by 2035.[47]

Figure 13: Opportunities for hydrogen in industrial processes

Petrochemicals	Hydrogen is currently used for cleaning and upgrading fossil fuels through hydrotreating. This demand could be displaced with clean hydrogen.
Metals processing	Traditional steelmaking methods depend on reacting iron ore with coal. New processes are being developed that use hydrogen instead.
Food manufacturing	In the food industry, hydrogen is used to harden oils and semisolid fats through hydrogenation. This demand could be displaced with clean hydrogen.
Synthetic fuels	Hydrogen is utilised to clean fuels and can be used to produce synthethic fuels like petroleum, diesel, methane and kerosene through reactions with CO_2.
Glass manufacturing	Hydrogen is currently used to provide an atmosphere during manufacturing that minimises glass flaws. This demand could be displaced with clean hydrogen.
Ammonia	Hydrogen is a key feedstock for ammonia production. This hydrogen demand could be displaced with clean hydrogen.
Chemicals	A range of chemicals utilise hydrogen as a feedstock, such as methanol, resins and polymers. This hydrogen demand could be displaced with clean hydrogen.

46 Vass, T., Fernandez-Pales, A., Levi, P. (2019) *Iron and Steel: Tracking Clean Energy Progress*. [Online] Available from: https://www.iea.org/tcep/industry/steel/ Accessed: 18/11/2019

47 Hybrit (n.d.). *HYBRIT – towards fossil-free steel*, [Online] Available from: http://www.hybritdevelopment.com/ Accessed: 18/11/2019

Finally, hydrogen presents an opportunity for synthetic fuel production as Australia is heavily dependent on the import of crude oil and crude based liquid fuels such as gasoline, diesel and jet fuel.[48] Hydrogen can be combined with CO_2 to synthetically produce any of these higher order liquid fuels as 'drop-in' alternatives, requiring no change in existing engine infrastructure.

2.5.2 Challenges and RD&D opportunities

The National Hydrogen Strategy Issues Papers highlighted several challenges that need to be overcome to optimise hydrogen for industrial users. These challenges included ensuring adequate and affordable hydrogen supply, appropriate regulations and standards, and availability of skills to support industrial users.[49] Outlined below are those where RD&D can play a role.

CHALLENGE	SWITCH CURRENT INDUSTRIAL USERS OF HYDROGEN TO ZERO OR LOW EMISSIONS HYDROGEN	
Context	Many industries, such as ammonia and petrochemicals, rely on hydrogen as part of their industrial process. For zero or low-emissions hydrogen to be incorporated in these industrial processes, organisation will need to consider a broad range of factors. For example, industrial users would require a reliable or constant supply of zero to low emissions hydrogen at the desired scale to ensure continual operations at a price point that does not negatively impact the cost of production. Depending on the volume required and the location of production, hydrogen storage and distribution may also require consideration. Variable renewables and ramping up and down of hydrogen production may require storage options. Hydrogen distribution via pipelines could allow hydrogen to be generated centrally at scale and delivered to multiple industrial (or non-industrial) hydrogen users. Pipelines could also be used to act as a short-term (ranging from days to a week) storage buffer in support of continuous operations.	
RD&D opportunities	**Production (Part 3.1)**	• Develop production technologies to meet operational requirements different industrial users (production volumes, reliability, flexibility and costs). Where on-site hydrogen production is used, hydrogen production technologies may need to be optimised to input or physical space requirements or constraints. • Develop production technologies that improve operations by leveraging process waste streams or making use of by-products from hydrogen production.
	Storage and distribution (Part 3.2)	• Identify and test suitable hydrogen storage and distribution technologies for different industrial user requirements (for example storage to provide a buffer to support continuous operations) • If pipelines used for distribution, understand pipeline requirements or further develop separation technologies (need for this activity dependent on context) (discussed in Gas networks opportunity – Part 2.2).
	Utilisation (Part 3.3)	• Undertake systems integration and analysis to understand equipment modification and requirements for users. For example, some users may not require high purity hydrogen for operations.
	Cross-cutting RD&D (Part 3.4)	• Conduct modelling to calculate and monitor the cost competitiveness of zero or low-emissions hydrogen against current inputs. This includes analysis to optimise and better align production and storage and distribution technologies. • Develop business models that consider clean hydrogen inputs and the impact on sales from becoming a premium "green" product. • Support the development of policy, regulations or schemes that certify hydrogen as zero or low-emissions. • Investigate the potential need to develop new safety guidelines or update existing guidelines. • Conduct environmental assessments and analysis for projects. For example, environmental considerations related to the integration of hydrogen production with CCUS or other carbon sequestration methods (where required).

48 Commonwealth of Australia (2019). *Liquid Fuel Security Review: Interim Report*, Department of the Environment and Energy, [Online] Available from: https://www.environment.gov.au/system/files/consultations/7cf6f8e2-fef0-479e-b2dd-3c1d87efb637/files/liquid-fuel-security-review-interim-report.pdf

49 National Hydrogen Strategy Taskforce (2019). *National hydrogen industry – Issues paper series – Hydrogen for industrial users*, Department of Industry, Innovation and Science, [Online] Available from: https://consult.industry.gov.au/national-hydrogen-strategy-taskforce/national-hydrogen-strategy-issues-papers/supporting_documents/NationalHydrogenStrategyIssue9HydrogenforIndustrialUsers.pdf

CHALLENGE	DEVELOP USE CASES TO ADAPT CURRENT PROCESSES TO USE HYDROGEN AND ITS DERIVATIVES	
Context	There are broad range of industrial processes that are dependent on emissions intensive feedstocks that could consider the use of zero to low emissions hydrogen to support decarbonisation efforts. However, a shift away from an existing feedstock is not a straight forward proposition and will require engineering, analysis, safety assessments, new technologies and strong business cases to support change. Furthermore, hydrogen is not the only way to decarbonise industrial process and analysis would be required to consider alternatives. As such, each of these processes would need to be considered on a case by case basis. The use of hydrogen in steel making was raised through interviews and provides a useful example to understand the process and consideration for hydrogen use. Conventional refining of iron ore to iron is conducted in a blast furnace using coking coal as both the primary energy source and reductant. Iron is then transformed into steel through the careful addition of oxygen, carbon and other trace elements. But it is the ironmaking step which has made steelmaking difficult to decarbonise. This is largely due to the dual role coke has in the blast furnace as a reductant as well as physical structure to support the blast furnace bed, giving it strength and porosity (and not being too reactive). Replacing coke with alternative materials that are effective and affordable is a challenge. While RD&D on hydrogen production, storage and distribution is valuable, RD&D related utilisation and in cross-cutting fields has been explored in greater detail due to the complexity of these different industrial process and the change required.	
RD&D opportunities	**Utilisation (Part 3.3)**	• Undertake systems integration and analysis to understand process redesign, equipment modification and other user requirements. • Explore opportunities to leverage hydrogen production by-products generated from different technologies (e.g. oxygen, chemicals, CO_2, or other hydrocarbons) within the industrial process. • Support Australian demonstration projects to understand process implications, scale up requirements and identify opportunities to reduce costs. For example, of hydrogen use in steelmaking this may include using the demonstrations to optimise reduction process parameters (e.g. temperature, pressure, gas composition).[50]
	Cross-cutting RD&D (Part 3.4)	• Conduct modelling and develop use cases that optimise how to optimise and better align production and storage and distribution technologies. • Develop accurate models that can predict the implications of process change. For example, process implications reduction behaviour of different reduction procedures and different input materials.[51] • Review and develop or refine Australian safety codes and standards to support Australian hydrogen use in steelmaking. These activities should aim to be consistent with international standards and learn from existing international demonstrations. • Evaluate environmental and community considerations to support the process change. For example, new skills that may be required and new jobs that could be created.

50 Spreitzer, D. and Schenk, J. (2019), *Reduction of Iron Oxides with Hydrogen—A Review*. steel research int., 90: 1900108. doi:10.1002/srin.201900108

51 Spreitzer, D. and Schenk, J. (2019), *Reduction of Iron Oxides with Hydrogen—A Review*. steel research int., 90: 1900108. doi:10.1002/srin.201900108

CHALLENGE	ESTABLISH NEW MARKET OPPORTUNITIES FOR ZERO OR LOW EMISSIONS HYDROGEN		
Context	Beyond the use of hydrogen within established and mature markets (discussed in previous challenges) are opportunities to support the establishment of new or emerging markets. These opportunities will be driven by economic and market requirements for hydrogen and its derivatives (and potentially supported by the saleable co-products from hydrogen production processes). While difficult to predict the opportunities (and RD&D needs), one example opportunity could be to progress synthetic fuel production techniques to expand carbon neutral fuel options. This opportunity can significantly reduce Australia's dependence on imported fuel by localising production. It also provides a significant market for utilisation of CO_2. Given that this process produces readily used liquid fuels that are 'drop-in', there are no major changes required for technologies and infrastructure related to storage and distribution and utilisation which supports the value proposition.		
RD&D opportunities		**Production (Part 3.1)**	• Develop high temperature hydrogen production technologies to maximise whole-of-system efficiencies due to the availability of waste heat in the synthetic fuel production process. For example, high temperature electrolysis will also allow for the direct production of syngas (as an intermediate) by directly electrolysing steam and CO_2. This obviates the need to apply the reverse-water-gas-shift reaction, effectively removing a step in the overall production process.
		Cross-cutting RD&D (Part 3.4)	• Develop and demonstrate CCUS technologies (for example capture technologies such as amines, MOFs and membranes) as production of synthetic fuels promotes the use of CO_2. An important part of this process will be the further development of direct air capture of CO_2 from the atmosphere given that it provides a flexible CO_2 source that can be paired with strong renewable resources and doesn't add to the carbon cycle.

3 Underpinning RD&D opportunities across the value chain

Part 2 explored opportunities in hydrogen export and the use of hydrogen in gas networks, for transport, supporting electricity systems and in industrial processes. It showed that each opportunity has specific market activation challenges that can be supported by RD&D. This part of the report considers the breadth of RD&D opportunities across the value chain:

Rather than picking winners, this report presents detailed analysis across the value chain in order to allow stakeholders in industry, research institutions and government agencies to make their own informed choices. The report, along with the Technical Repository,[52] explores a broad range of technologies and research areas in detail. Importantly, it has been designed to act as a resource that can evolve over time as technologies advance or as government and industry funding and priorities change.

Emerging themes

Several themes emerged through interviews and the analysis of industry challenges and underpinning RD&D opportunities across the value chain. This includes the need for RD&D diversity, a focus on cost and efficiency improvements, as well as breakthrough technology areas and the need to develop integrated decision-making support capability. Together these themes are important considerations for enhancing Australia's hydrogen RD&D ecosystem and shaping Australia's emerging industry.

52 Charnock, S., Temminghoff, M., Srinivasan, V., Burke, N., Munnings, C., Hartley, P. (2019). *Hydrogen Research, Development and Demonstration: Technical Repository*, CSIRO.

Theme 1: Diverse industry challenges and solutions require diverse RD&D capability

The complexity and diversity of hydrogen industry challenges and possible pathways requires a diverse range of RD&D capability to match. This includes deep technical expertise in hydrogen related technologies, complemented by expertise in cross-cutting RD&D fields. This diverse RD&D capability should be developed and strategically leveraged to collaboratively respond to global and domestic industry opportunities. Together, diverse teams will help foster near term and breakthrough technologies and create new knowledge that helps the global industry develop.

Analysis of technologies from across the value chain is provided to allow stakeholders in industry, research and government to make informed choices. Over time, Australia's RD&D capability can be further refined or focused as the industry matures and investment in specific opportunities increases.

Understanding current active hydrogen projects can be used to indicate existing capability that could be leveraged and readily transferred into new RD&D areas (see Figure 14). However, it should also be emphasised that this summary acts as a snapshot only. As such, it does not capture existing capability that could be readily transferred from one area of research into another, nor knowledge

Figure 14: Snapshot of current hydrogen RD&D project activity

Hydrogen production	
Electrolysis	12
Fossil fuel conversion	12
Biomass and waste conversion	11
Direct hydrogen carrier production	4
Thermal water splitting	5
Biological hydrogen production	9
Photochemical and photocatalytic processses	16

Cross-cutting RD&D	
Environment	5
Social licence, safety and standards	13
Modelling	15
Policy and regulation	6
Ancillary technology and services	12

Storage and distribution	
Compression and liquefaction	13
Compressed hydrogen	6
Liquid hydrogen	6
Underground storage	4
Pipeline storage	5
Chemical storage	17
Ammonia	10
Synthetic fuels	10
Liquid organic hydrogen carriers	5
Hydrides	11
Proton batteries	3
Physisorption	9

Hydrogen utilisation

Hydrogen application-specific technologies including technologies for:

Hydrogen utilisation	14
Direct hydrogen carrier utilisation	4

For further details refer to Hydrogen Research, Development and Demonstration: Technical Repository and experience that may have been developed in a given institution over time. Furthermore, hydrogen RD&D is expected to change rapidly over the coming years, as will capabilities that emerge with new projects and researchers. Ideally, this summary should be maintained regularly to hold an accurate picture of the Australian hydrogen RD&D landscape.

Theme 2: RD&D to deliver cost and efficiency improvements will be a critical success factor

Achieving low-cost production of hydrogen at scale will be a critical factor for determining the growth and success for the hydrogen industry. This analysis identified a broad range of cost and efficiency opportunities across the value chain which are achievable through RD&D (see Figure 15). From a cost perspective, there are specific opportunities to reduce capital and operating costs through new materials, system designs and improvements in integration between technologies. While inherently linked to cost, efficiency is particularly important for making the most out of the resources available.

Figure 15: Example cost and efficiency opportunities for RD&D

Hydrogen production

- **Reactor or stack improvements** through new materials and designs for greater durability, lower cost, operation at desirable conditions, etc.
- **Integration and key process improvements** to power sources, production stacks and storage systems.
- **Balance of plant reductions** through actions such as operating condition optimisation, heat source integration, complimentary technology co-location, etc.

Storage and distribution

- **Storage materials and system designs** to improve hydrogen storage capacity, costs, material life and round-trip energy efficiency; and enhance applicability to specific use-cases.
- **Synthesis methods** to optimise reactor materials, conditions and efficiency at lower costs where hydrogen carriers are used.
- **Compression methods** to improve hydrogen compression costs and efficiency.

Hydrogen utilisation

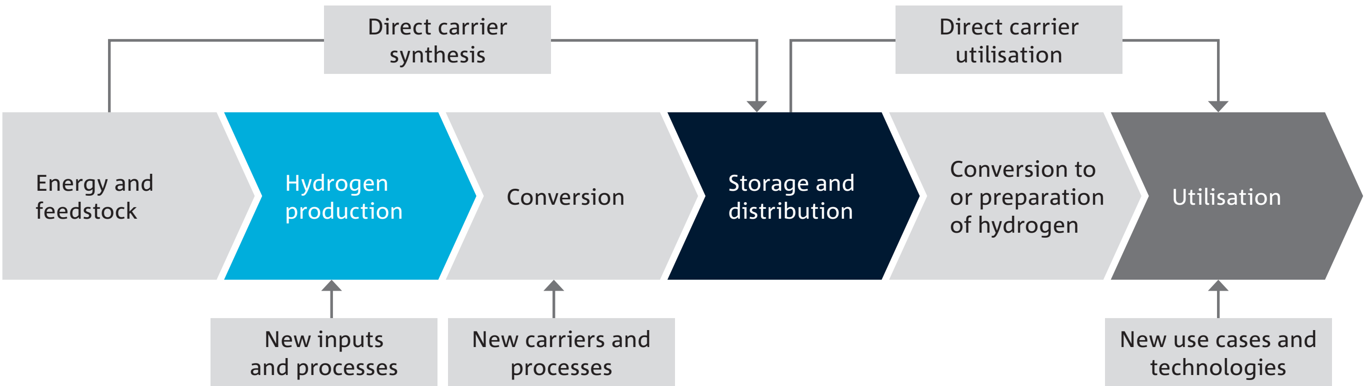
- **Stack improvements** through development of new materials and designs for electrolytes, catalysts, gas diffusion media and cell hardware.
- **Balance of plant improvements** to reduce costs and increase durability of components including humidifiers, compressors and fuel processors.
- **Turbine durability and function improvements** with development of heat resistant materials, management of combustion profiles and emissions reductions.

Theme 3: RD&D in breakthrough technology areas, including in hydrogen utilisation, can lead to step-change cost reductions or process improvements across the value chain

Identifying and developing breakthrough technologies can offer step-change benefits across the hydrogen value chain. This could include eliminating the need to process a given feedstock for hydrogen production, for example by using low quality or waste water inputs without pretreatment. Breakthrough technologies could also allow the use of alternative feedstocks such as biomass or waste streams; or value chain transformation for example through direct use of carriers (see Figure 16). While difficult to predict the timeline of such developments, RD&D on new hydrogen generation or storage technologies could lead to breakthroughs that change cost structures or reduce or eliminate process steps.

A key opportunity is in the development of new hydrogen utilisation technologies, particularly in large scale industrial settings. Such technologies will serve to boost demand and help encourage cost reductions in hydrogen production, storage and distribution as well as in ancillary technologies and services that are required to support the industry.

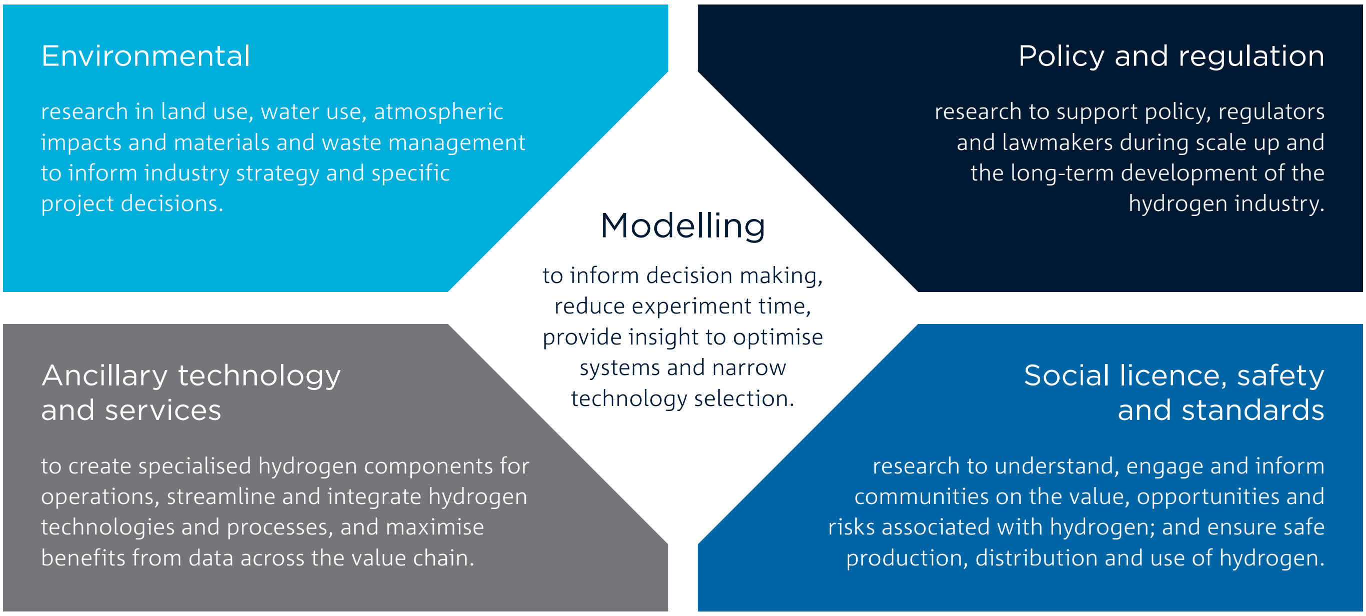
Figure 16: Example breakthrough opportunity areas



Theme 4: Integrated decision-making support through research in cross cutting areas can de-risk project development and deliver industry outcomes

The development of Australia's hydrogen industry will be strengthened by information and decision-making support across five cross-cutting RD&D fields (see Figure 17), discussed further in Part 3.4. While each of these fields are often viewed independently, they are interrelated and collaboration across these fields will be important to achieving greater industry and economy-wide outcomes. Integrated approaches to decision making has the potential to lead to more efficient industry development, drive new opportunities and help to understand dividends for the entire economy.

Figure 17: Cross-cutting RD&D fields



3.1 Hydrogen production

Hydrogen production RD&D should focus on lowering costs, improving production efficiency and enhancing safety and sustainability to support a range of end-uses.

3.1.1 Introduction

There is a wide range of hydrogen production technologies at various levels of maturity, each requiring different feedstocks, energy inputs and operating conditions.
To aid understanding, this section has been structured by production process (see Figure 18):

- **Electrolysis** – An electric current is applied to split water into hydrogen and oxygen gas streams.
- **Fossil fuel conversion** – Elevated temperatures are used to generate hydrogen and a range of possible by-products from a fossil fuel resource (natural gas, coal, or oil).
- **Biomass and waste conversion** – Elevated temperatures are used to produce hydrogen and other products from biomass or municipal waste streams.
- **Direct hydrogen carrier production** – Instead of producing hydrogen, a chemical hydrogen carrier is synthesised directly from feedstock other than hydrogen. The chemical carrier can be utilised directly in some applications or used as a means to store and distribute hydrogen which can later be extracted for use.
- **Thermal water splitting** – Elevated temperatures are used for the direct or chemically-assisted splitting of water into hydrogen and oxygen gas streams.
- **Biological hydrogen production** – Biological materials, pathways, or systems photosynthesise or convert organic matter to produce hydrogen and other products.
- **Photochemical and photocatalytic processes** – Sunlight is used by photovoltaic or photocatalytic materials, which split water into hydrogen and oxygen gas streams, without the use of an external electric circuit.

Due to the different processes involved, technologies have different RD&D priorities that need to be pursued in order to reduce costs, boost efficiencies and facilitate system integration. Suitability of the production process depends on the requirements of end use and available resources.

To inform decision making, each of these technologies is supported by a technology repository which provides further detail into each technology (see Technical Repository[53]).

Figure 18: Hydrogen production processes

Electrolysis	Fossil fuel conversion	Biomass and waste conversion	Direct chemical carrier production	Thermal water splitting	Biological hydrogen production	Photochemical and photocatalytic processes
e.g. PEM electrolysis	e.g. Natural gas pyrolysis	e.g. Biomass gasification	e.g. Electrochemical ammonia synthesis	e.g. Solar-thermochemical water splitting	e.g. Dark fermentation	e.g. Photocatalytic water splitting

53 Charnock, S., Temminghoff, M., Srinivasan, V., Burke, N., Munnings, C., Hartley, P. (2019). *Hydrogen Research, Development and Demonstration: Technical Repository*, CSIRO.

Hydrogen production RD&D priorities

The following high-level RD&D priorities apply across all hydrogen production processes:

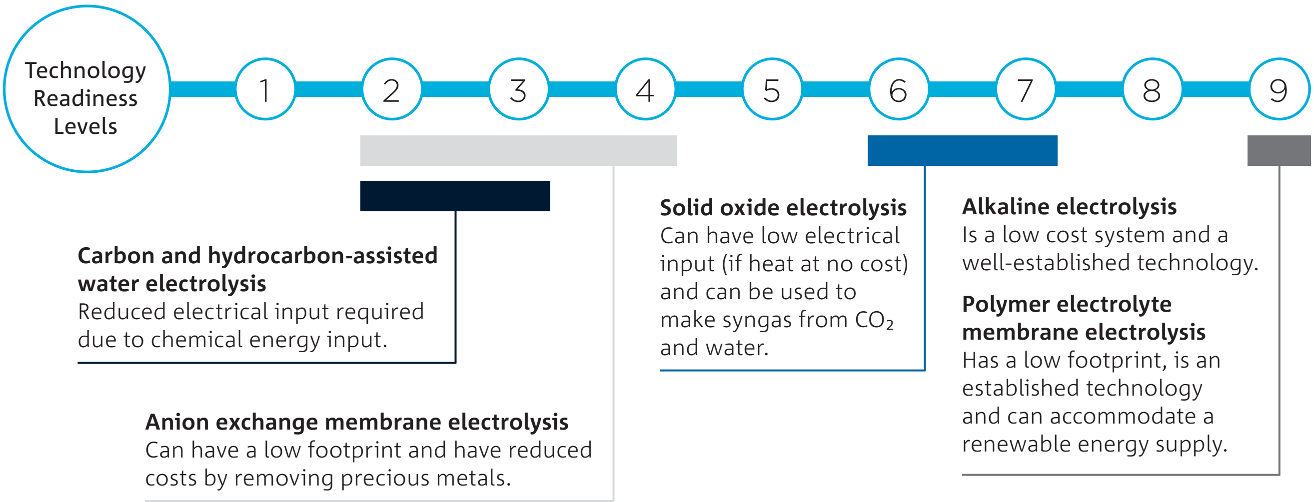
- **Reactor or stack** improvements through new materials and designs for greater durability, lower cost, operation at desirable conditions, manufacturing improvements and higher hydrogen production performance.
- **Key process** improvements through effective integration of components such as power sources, production stacks and storage systems.
- **Balance of plant** reductions through actions such as operating condition optimisation, heat source integration, complimentary technology co-location, automation to facilitate co-location, and reduced need for external components.
- **Environmental** research to achieve zero-to-low net carbon emissions (e.g. CCUS), reduce lifecycle impacts through recycling and reuse of chemical inputs and assessment of land use, water use, atmospheric impacts.
- **Health and safety** research such as the use of safer chemicals, equipment and operating conditions, and mechanisms to effectively handle reactive product gas streams (i.e. hydrogen and oxygen). Additionally, research and modelling of production plant implementation in distributed urban settings.
- **Social licence** research into community acceptance of hydrogen production facilities and use in public contexts (e.g. transport and gas networks).

3.1.2 Electrolysis

In electrolytic methods, an electric current is applied to split water into hydrogen and oxygen gas streams. The process typically occurs in a device known as an electrolyser (comprised of a 'stack'), in which hydrogen gas is produced at the positively charged cathode and oxygen gas is produced at the negatively charged anode. Given that electricity is the primary energy source, to be considered low to zero emission they must be connected to renewable energy sources, sourced through a purchase power agreement, or connected to a hybrid power supply with integrated CCUS.

The high-maturity technologies include alkaline electrolysis (AE) and polymer electrolyte membrane (PEM) electrolysis. While commercial, these technologies could still be improved through RD&D advancements such as improved energy efficiency, production rate, stack life, or reduced capital costs. The low maturity technologies make use of alternative membranes (anion exchange membrane electrolysis, solid oxide electrolysis) or energy sources (carbon and hydrocarbon-assisted water electrolysis, solid oxide electrolysis) to drive hydrogen production. The use of an additional energy input provides the advantage of reducing the required electrical energy input to produce hydrogen, or the ability to make use of a currently underutilised energy source such as waste heat. Figure 19 showcases the technologies within this category, along with their respective TRLs and a key benefit for each.

Figure 19: Electrolysis technologies



RD&D priorities

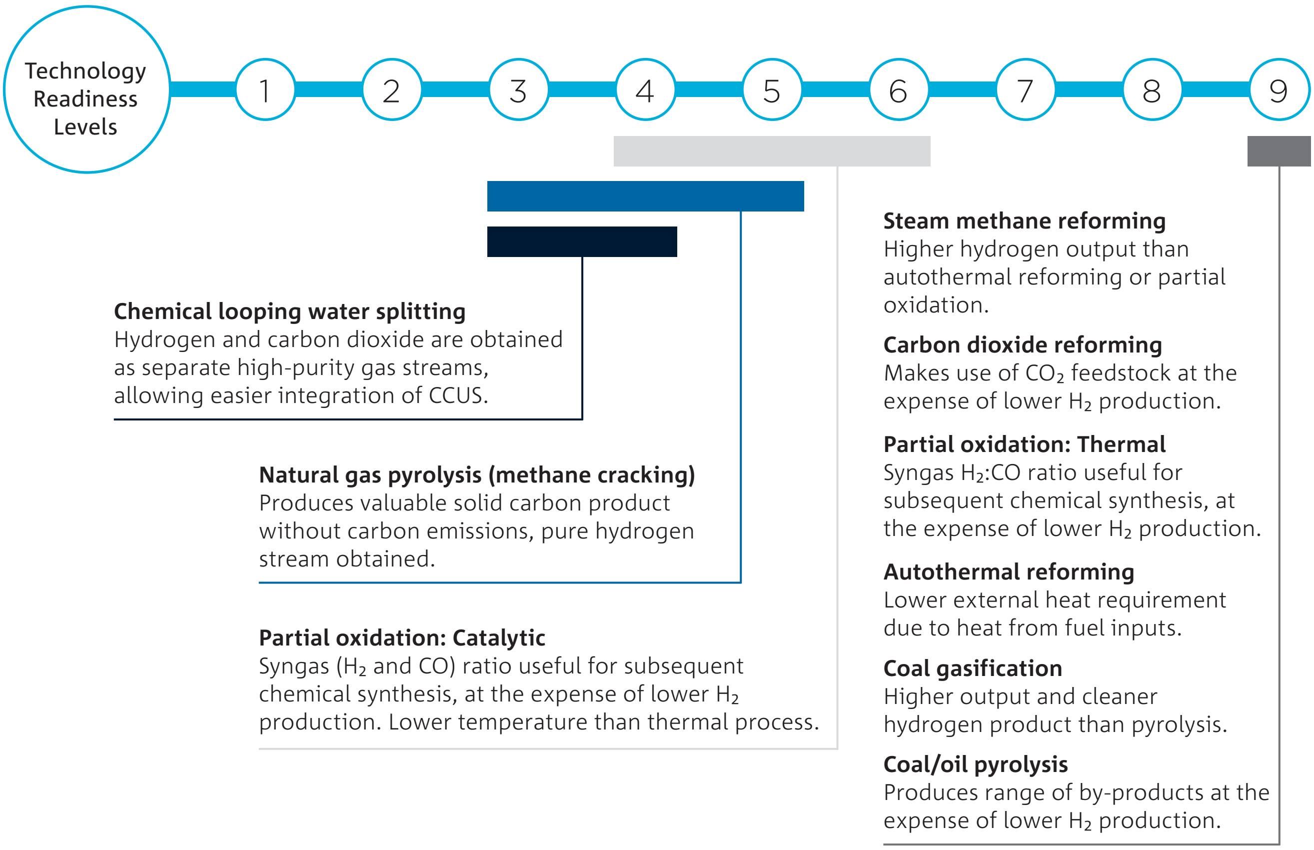
RD&D PRIORITY AREAS	FACTORS
Cost and efficiency	**Reactor design**
	• Improve stack design for reduced footprint • Develop and test non-precious catalysts and electrodes (particularly PEM) • Develop lower cost membranes (PEM, SOE, AEM) • Develop higher durability electrodes and membranes (SOE, AEM, carbon and hydrogen-assisted water electrolysis) • Improve manufacturing processes for reduced capital cost • Achieve higher pressure hydrogen as a compressed gas output
	Balance of plant
	• Optimise cell, stack, and plant design for greater flexibility in ramping up and ramping down (AE, SOE) • Achieve lower temperature operation to allow use of low-grade waste heat and reduce energy costs (SOE) • Achieve higher temperature operation to achieve higher production efficiency (AE, PEM) • Achieve higher pressure operation (SOE, AE, PEM) • Improve renewable energy integration and increase renewable energy conversion efficiency
Cross-cutting RD&D fields	**Environmental**
	• Design pathways or procedures for environmentally suitable treatment of cell materials at end of life • Conduct and continually update ecological assessments to ensure production facilities and operations have minimal impact on local environment
	Social licence and safety
	• Develop hydrogen sensors to detect leaks in production plants • Develop cells to make use of non-corrosive electrolytes (AE)

3.1.3 Fossil fuel conversion

Fossil fuel-based processes convert fossil fuels such as coal, natural gas, and oil into hydrogen and other chemicals. Many fossil fuel-based thermochemical plants are already established at industrial scale, with steam methane reforming being used for the majority of hydrogen production today. In order to achieve zero-to-low net carbon emissions, all fossil fuel-based technologies must be integrated with carbon capture, utilisation and storage (CCUS) mechanisms. The necessity for CCUS with fossil-fuel derived hydrogen results results in additional costs. One of the most important RD&D areas for higher TRL fossil fuel conversion technologies is improved CCUS mechanisms to reduce capture costs and potentially to increase the value of utilised CO_2. Any heat sources used in fossil fuel conversion process can also be substituted with concentrated solar thermal energy, presenting an opportunity to further integrate renewable energy and reduced carbon dioxide production for these processes.

Lower TRL technologies in this category could yield other benefits if made viable. For example, natural gas pyrolysis produces a valuable solid carbon product rather than CO_2, and chemical looping water splitting allows high purity hydrogen and carbon dioxide gas as outputs. Figure 20 showcases the technologies within this category, along with their respective TRLs and a key benefit for each.

Figure 20: Fossil fuel conversion technologies



RD&D priorities

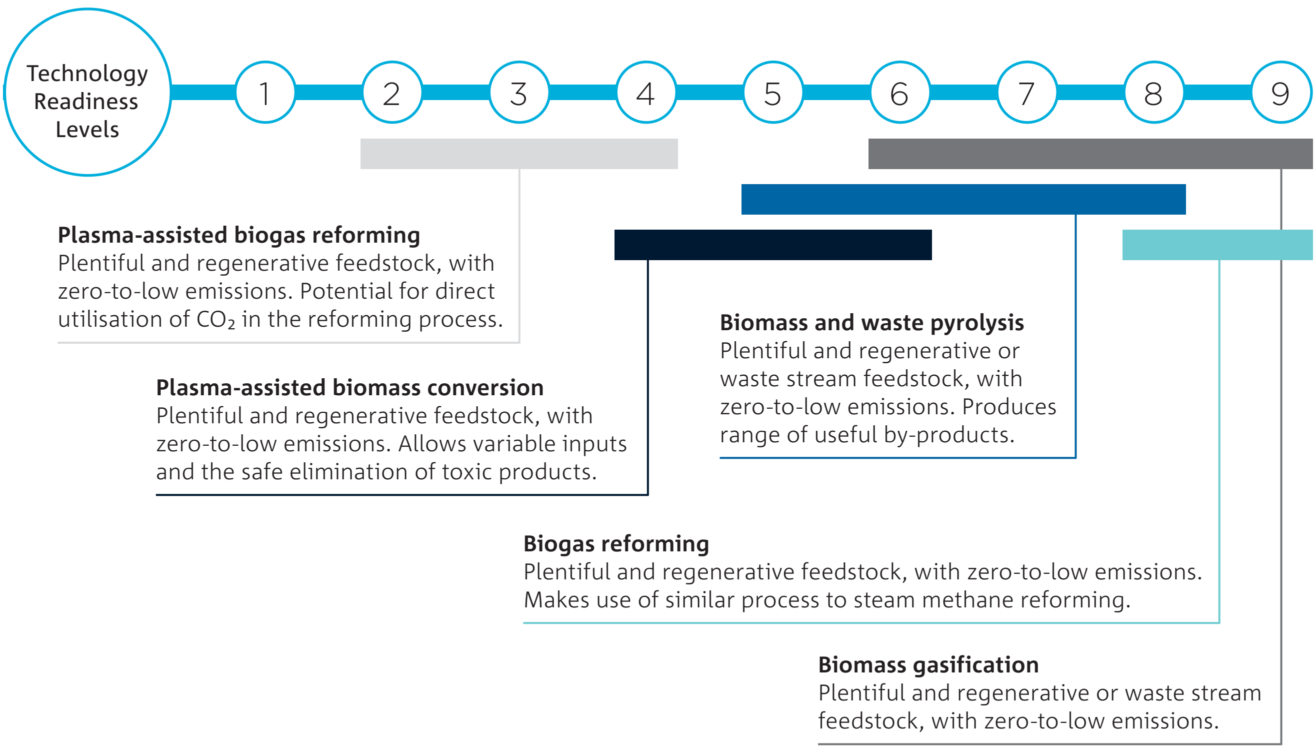
RD&D PRIORITY AREAS	FACTORS
Cost and efficiency	**Reactor design**
	• Develop non-precious-metal catalysts and electrodes (applies primarily to methane cracking mainly because it is lower on the TRL scale, however all processes can benefit from improved catalytic materials) • Design reactors to accommodate highly exothermic or endothermic reactions (e.g. staged introduction of reagents, better designed heat transfer surfaces, process intensification, reaction monitoring and control, pre-treatment of waste streams) • Develop advanced materials of construction for improved reactor performance and lifetimes, and reduced capital costs
	Balance of plant
	• Improve appliance and plant design for greater flexibility in ramping up and ramping down • Achieve higher or lower temperature operation to minimise energy costs • Demonstrate renewable energy integration (i.e. concentrating solar fuels technology) • Integrate sources of low-cost, low-carbon, high temperature heat for endothermic reactions • Achieve higher pressure operation for higher throughput per unit volume operation
Cross-cutting RD&D fields	**Environmental**
	• Develop and test effective means of integrating carbon capture, utilisation and storage (CCUS) to achieve zero-to-low carbon emissions • Reduce water usage • Design pathways or procedures for environmentally suitable treatment of waste by-products • Conduct and continually update ecological assessments to ensure production facilities and operations have minimal impact on local environment
	Social licence and safety
	• Develop hydrogen sensors to detect leaks in production plants
	Ancillary technology and services
	• Lower the cost of hydrogen separation systems designed to obtain hydrogen of an appropriate purity for specific applications

3.1.4 Biomass and waste conversion

Biomass-based and waste-based processes convert a biomass or municipal waste source (such as agriculture crop residues, forest residues, plantation crops, municipal organic waste, and animal wastes) into hydrogen and other chemicals.[54] Municipal solid waste, such as plastics and used tyres, can also be processed via gasification or pyrolysis to generate syngas.[55] Generally the conversion of waste is associated with a slightly lower TRL than typical woody biomass conversion processes. Biomass processes are typically less carbon intensive than fossil-based processes and could be considered to generate zero-to-low carbon emissions if they are from a waste biomass source, or negative emissions if from a waste and CCUS is employed. One of the key advantages of biomass and waste conversion is the ability to make use of a waste stream (agricultural biomass or municipal wastes) to generate a valuable hydrogen product or an intermediate product, which can be used for further chemical synthesis. Any heat sources used in biomass and waste conversion process can also be substituted with concentrated solar thermal energy, presenting an opportunity to further integrate renewable energy and reduced carbon dioxide production. A drawback for biomass and waste conversion methods is the variability in feedstock quality and the potential need for pre-treatment before processing.

Plasma-assisted biogas reforming and plasma-assisted biomass conversion methods allow for utilisation of electricity as an energy source for the processes and could enable smaller-scale conversion systems. Figure 21 showcases the technologies within this category, along with their respective TRLs and a key benefit for each.

Figure 21: Biomass and waste conversion technologies



54 US Department of Energy (2019). *Hydrogen Production: Biomass Gasification*. [Online] Available from: https://www.energy.gov/eere/fuelcells/hydrogen-production-biomass-gasification Accessed: 18/11/2019

55 Zhenling L. (2019). *Gasification of municipal solid wastes: a review on the tar yields*, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 41:11, 1296-1304, DOI: 10.1080/15567036.2018.1548508

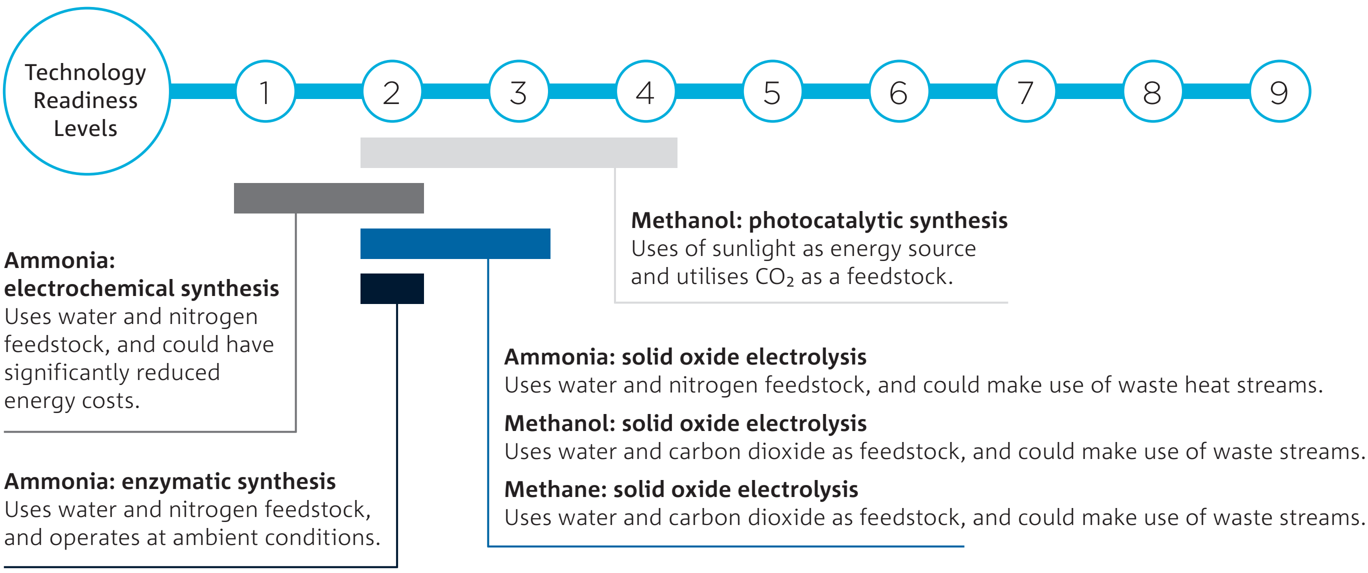
RD&D priorities

RD&D PRIORITY AREAS	FACTORS
Cost and efficiency	**Reactor design**
	• Optimise processes and address challenges related to different biomass feedstock characteristics (e.g. optimising process handling, improving anaerobic digestion process, investigating the effects of rapid heating on feedstock decomposition, etc.) • Improve reactor design and optimise operating parameters for greater energy efficiency (e.g. optimising temperature, catalyst characteristics, process intensification, selectivity, etc.). Depending on the technology and end-use requirements, this could include process miniaturisation for distributed use • Develop and optimise catalysts for given feedstocks • Develop advanced materials of construction for improved reactor performance and lifetimes, and reduced capital costs
	Balance of plant
	• Improve appliance and plant design for greater flexibility in ramping up and ramping down • Demonstrate renewable energy integration (i.e. concentrating solar fuels technology)
Cross-cutting RD&D fields	**Environmental**
	• Develop and test effective means of integrating carbon capture, utilisation and storage (CCUS) to achieve zero-to-low carbon emissions or take advantage of opportunities for negative emissions • Design pathways or procedures for environmentally suitable treatment of waste by-products • Conduct ecological assessments to ensure production facilities and operations have minimal impact on local environment
	Modelling
	• Conduct technoeconomic analysis to determine effective supply chain pathways for transporting feedstocks from point of origin to hydrogen production plants (e.g. mechanisms and routes to deliver municipal waste to a gasification plant)
	Ancillary technology and services
	• Lower the cost of hydrogen separation systems designed to obtain hydrogen of an appropriate purity for specific applications

3.1.5 Direct hydrogen carrier production

After hydrogen is produced, it can be converted into a variety of chemicals, named 'hydrogen carriers', to improve ease of storage and distribution to the point of utilisation. In the case of direct hydrogen carrier production, some of these carriers can be synthesised directly without the need for the typical precursor hydrogen production step. The chemical carrier can then be used to store and distribute hydrogen or utilised directly in some applications. Direct carrier syntheses present the opportunity to side-step hydrogen production, which could reduce capital equipment costs associated with reduced system components and complexity. It could also allow reduced energy costs associated with the chemical conversion to and from hydrogen gas. In other words, this would skip the production step of the hydrogen value chain. Direct production of hydrogen carriers also presents the opportunity to reduce costs related to capital. Note that this category is not distinguished by the feedstock (as a variety can be used), nor the process employed. Figure 22 showcases the technologies within this category, along with their respective TRLs and a key benefit for each.

Figure 22: Direct hydrogen carrier production technologies



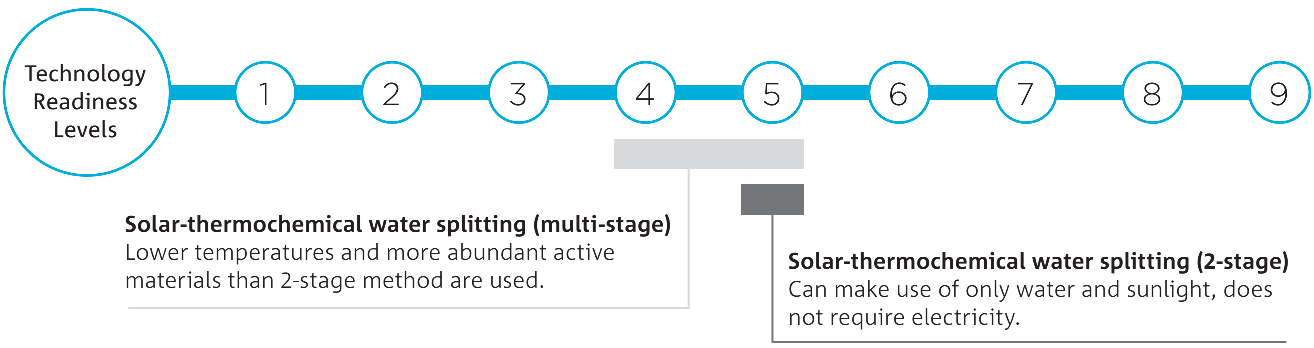
RD&D priorities

RD&D PRIORITY AREAS	FACTORS
Cost and efficiency	**Reactor design**
	• Achieve production rates and efficiencies that are competitive with conventional hydrogen production and carrier synthesis steps • Develop catalysts to improve selectivity to carrier product • Conduct investigations to understand fundamental reaction mechanisms
	Balance of plant
	• Improve system design and integration to ensure efficient transfer of heat (solid oxide syntheses)
Cross-cutting RD&D fields	**Environmental**
	• Conduct and continually update ecological assessments to ensure production facilities and operations have minimal impact on local environment
	Modelling
	• Conduct technoeconomic modelling to assess feasibility over current pathways

3.1.6 Thermal water splitting

Thermal water splitting employs elevated temperatures and are used for the direct or chemically-assisted splitting of water into hydrogen and oxygen gas streams. In solar-thermochemical water splitting, concentrated sunlight from a dish or mirror array is used to generate sufficient heat to drive a series of chemical reactions to split water into hydrogen and oxygen. These technologies are advantageous due to the utilisation of heat from direct sunlight as an energy source, and for having zero-to-low associated carbon emissions. It is also possible to source the heat required for thermochemical processes from nuclear power, however this technology is not covered in detail in this study. While currently at TRL 5, a project for construction of the first solar-thermochemical hydrogen demonstration plant in Australia is underway.[56] Figure 23 showcases the technologies within this category, along with their respective TRLs and a key benefit for each.

Figure 23: Thermal water splitting technologies



RD&D priorities

RD&D PRIORITY AREAS	FACTORS
Cost and efficiency	**Reactor design**
	• Improve concentrated solar thermal technologies • Improve long-term stability and durability of reactant materials for operation over large temperature ranges • Improve thermal efficiency • Conduct fundamental material investigations to understand mechanisms such as material melting and sticking (two-stage)
	Balance of plant
	• Develop large-scale system concepts
Cross-cutting RD&D fields	**Environmental**
	• Conduct and continually update ecological assessments to ensure production facilities and operations have minimal impact on local environment
	Social licence and safety
	• Develop hydrogen sensors to detect leaks in production plants

56 Australian Renewable Energy Agency (2019). *Solar Thermochemical Hydrogen Research and Development.* [Online] Available from: https://arena.gov.au/projects/solar-thermochemical-hydrogen-research-and-development/ Accessed: 18/11/2019

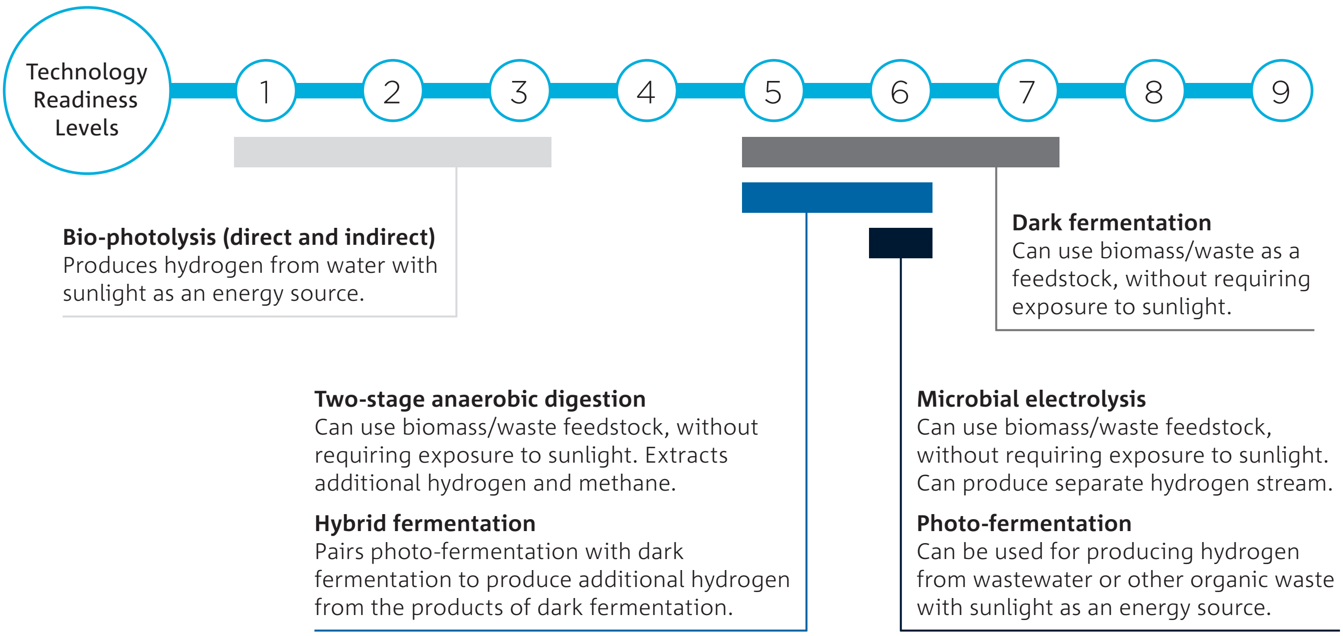
3.1.7 Biological hydrogen production

Biological hydrogen production involves the conversion of organic matter into hydrogen and other products via biological processes. Specifically, the nitrogenase and hydrogenase enzymes present in many bacteria engage in fermentation or photosynthesis to break down biomass into hydrogen and oxygen, carbon dioxide, or other organic compounds. The main advantage of these methods is the ability to convert a biomass or municipal waste stream into a usable energy source. Broadly, biological hydrogen technologies can be divided into those which are driven by light, and those which are independent of light and instead driven solely by biological activity.

- **Light-driven systems** include photosynthetic and photo-fermentative process which require energy from sunlight. As a result, they do not require intermediary energy convertors (e.g. solar PV systems), but nonetheless require a large surface area due to the need for direct solar irradiation. Most of these technologies face the current challenges of low sunlight-hydrogen energy conversion efficiency, production rates and yields.
- **Light-independent systems** operate irrespective of solar irradiation, and therefore require a lower surface area and could operate irrespective of solar intermittency. While dark fermentation is driven by energy from biological processes, microbial electrolysis is in part driven by an electric current which requires an external power source. These systems also face challenges associated with production rates and yields.

Figure 24 showcases the technologies within this category, along with their respective TRLs and a key benefit for each.

Figure 24: Biological hydrogen production technologies



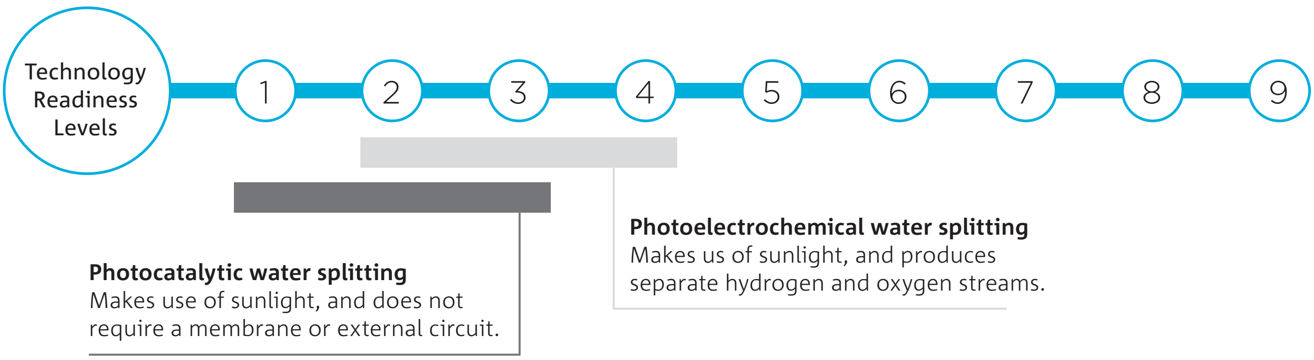
RD&D priorities

RD&D PRIORITY AREAS	FACTORS
Cost and efficiency	**Reactor design**
	• Develop higher durability cell materials (bio-photolysis, dark fermentation) • Develop inexpensive bioreactors (photo-fermentation, hybrid fermentation, bio-photolysis) • Develop inexpensive cathodes (microbial electrolysis) • Optimise reactor conditions (dark fermentation) • Improve substrate conversion efficiency (hybrid fermentation) • Increase current density (microbial electrolysis) • Conduct metabolic engineering of bacteria to improve hydrogen production performance (dark fermentation, photo-fermentation) • Develop an oxygen-resistant hydrogenase (bio-photolysis) • Develop measures to prevent further biological conversion of hydrogen into other compounds such as methane gas (microbial electrolysis) • Improve the selectivity of hydrogen production • Improve the solar-to-hydrogen energy conversion efficiency (light-dependent methods)
	Balance of plant
	• Improve renewable energy integration and increase renewable energy conversion efficiency (microbial electrolysis)
Cross-cutting RD&D fields	**Environmental**
	• Design pathways or procedures for environmentally suitable treatment of cell materials and electrolytes • Conduct and continually update ecological assessments to ensure production facilities and operations have minimal impact on local environment
	Social licence and safety
	• Develop hydrogen sensors to detect leaks in production plants
	Ancillary technology and services
	• Lower the cost of hydrogen separation systems designed to obtain hydrogen of an appropriate purity for specific applications

3.1.8 Photochemical and photocatalytic processes

Photoelectrochemical and photocatalytic water splitting processes involve the use of sunlight to directly split water into hydrogen and oxygen. Note that while driven by solar energy, these processes do not rely on generation of high temperatures and are therefore distinct from solar-thermochemical technologies. These methods have the advantage of being able to use sunlight alone as an energy source without requiring electrical energy input. The systems allow minimal energy conversions and low associated zero-to-low carbon emissions. However, these technologies require large surface areas, are low TRL and currently difficult to scale. Figure 25 showcases the technologies within this category, along with their respective TRLs and a key benefit for each.

Figure 25: Photochemical and photocatalytic hydrogen production technologies



RD&D priorities

RD&D PRIORITY AREAS	FACTORS
Cost and efficiency	**Reactor design**
	• Photocatalyst and co-catalyst materials development for lower cost and improved durability • System design for large scale hydrogen production. Includes particle immobilisation schemes and reactor designs. • Improve manufacturing processes for reduced capital cost
	Balance of plant
	• Systems integration and design • Improve the solar-to-hydrogen energy conversion efficiency
Cross-cutting RD&D fields	**Environmental**
	• Design pathways or procedures for environmentally suitable treatment of cell materials and electrolytes • Conduct and continually update ecological assessments to ensure production facilities and operations have minimal impact on local environment
	Social licence and safety
	• Develop hydrogen sensors to detect leaks in production plants
	Ancillary technology and services
	• Lower the cost of hydrogen separation systems designed to obtain hydrogen of an appropriate purity for specific applications (photocatalytic)

3.2 Hydrogen storage and distribution

Hydrogen storage and distribution RD&D should focus on lowering costs and improving storage capacity and roundtrip energy efficiency for multiple end-uses.

3.2.1 Introduction

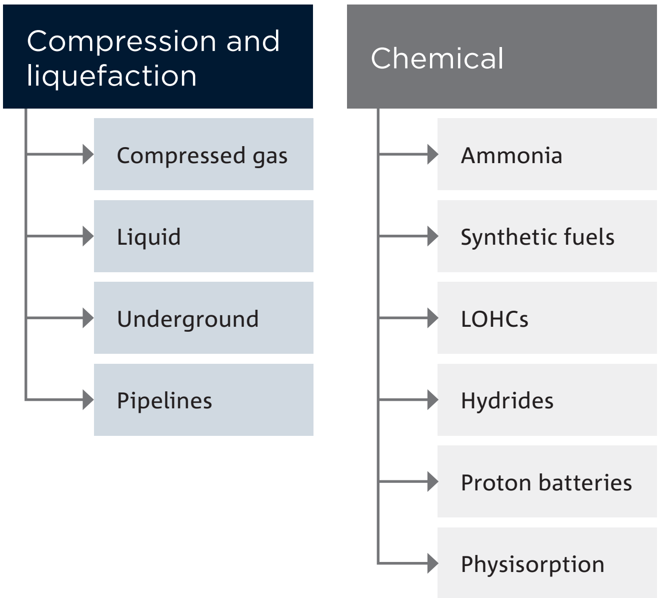
The selection of hydrogen storage and distribution pathways requires consideration of the following factors: volumetric and gravimetric density (hydrogen capacity in a given volume and percentage of storage system weight), operating conditions, distribution requirements, customer end-use requirements, and cost and availability of storage materials. It also requires consideration of the roundtrip process costs and energy efficiency, i.e. the overall process and energy costs associated with storing hydrogen within the vessel or carrier, and safely extracting it for use.

To support decision making this section has been structured by the following two classes (see Figure 26):

- **Compression and liquefaction:** The compression or liquefaction of hydrogen and storage in pressurised containment vessels, pipeline, or underground. Conversion to or bonding with another chemical is not required.
- **Chemical:** Conversion to or storage of hydrogen within another chemical or material, which acts as a hydrogen carrier for denser storage and transport. Hydrogen can later be extracted from the carrier for use, or in some cases the carrier itself can be utilised directly.

To inform decision making technologies in each class are supported by a side by side comparison of each production technology and a technology repository which provides further detail into each technology (see Technical Repository).

Figure 26: Hydrogen storage and distribution classes



Hydrogen storage and distribution RD&D priorities

- Storage materials and system designs to improve hydrogen storage capacity, costs, material life and round-trip energy efficiency; and enhance applicability to specific use-cases (storage conditions, density, etc.).
- Synthesis methods to optimise reactor materials, conditions and efficiency at lower costs where hydrogen carriers are used.
- Compression methods to improve hydrogen compression costs and efficiency.
- Environmental research to reduce or eliminate environmental impacts from production of storage materials, mitigate spillage risks and impacts to marine environments, and CCUS research where required for hydrogen carrier synthesis.
- Health and safety research to prevent injury from storage systems or exposure to toxic carriers such as LOHCs.

3.2.2 Compression and liquefaction

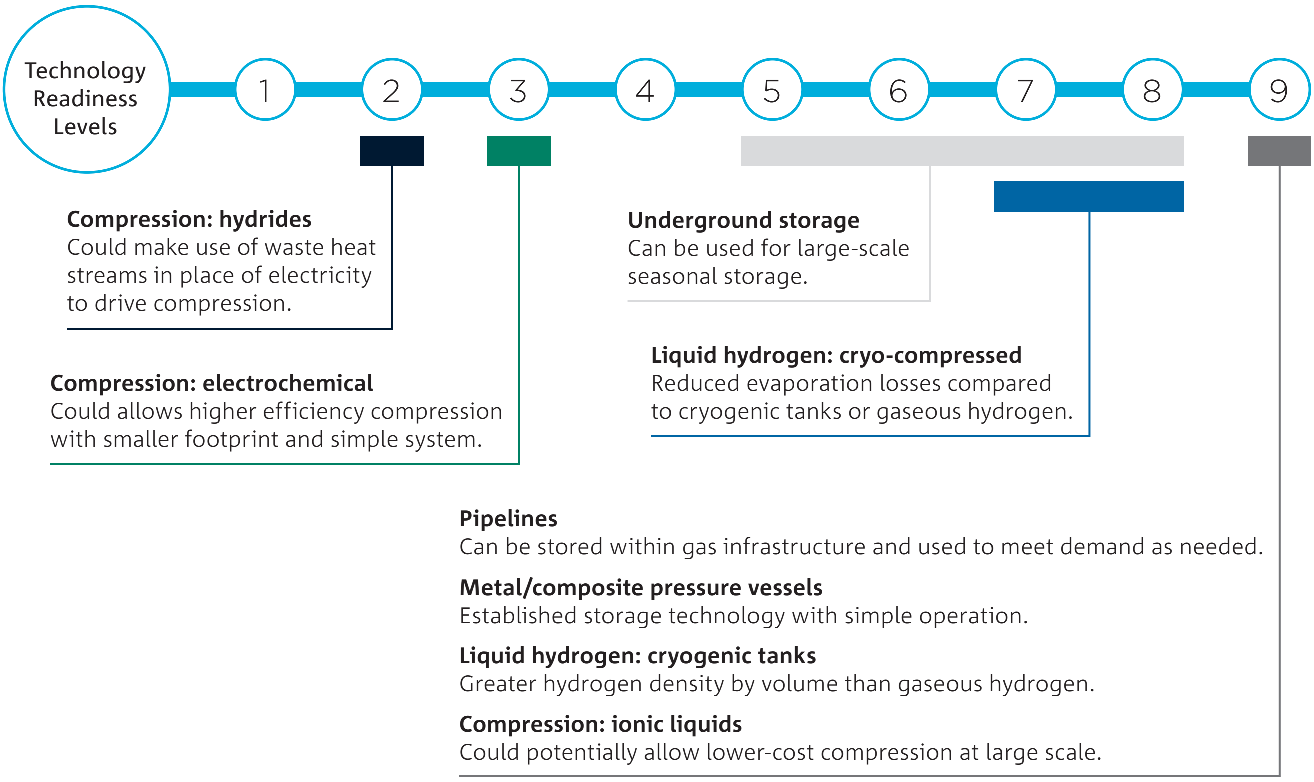
Technology overview

Hydrogen is compressed or liquefied for storage, without requiring conversion to or bonding with another chemical. This type of storage is the incumbent technology used for storage and distribution of hydrogen (see Figure 27).

This category is divided into compressed hydrogen gas in vessels, liquid hydrogen in vessels, gaseous hydrogen stored in pipelines or gaseous hydrogen stored underground. All technologies in this category benefit from higher-efficiency compression mechanisms (described in detail in Technical Repository).

- **Compressed hydrogen gas** – Hydrogen is stored at high pressures (up to 800 bar) in steel or carbon fibre composite tanks. This form of storage is the most established and is already employed in commercially available hydrogen fuel cell electric vehicles (FCEVs). Mechanical compression is already widely used, however new approaches such as electrochemical, ionic liquid, and hydride compression are being developed to improve the efficiency of the storage process.
- **Liquid hydrogen** – Hydrogen is stored at cryogenic temperatures (-253°C) and ambient or high pressures as a liquid, which offers far greater volumetric density when compared to hydrogen in a gaseous state; and greater gravimetric density when accounting for the containment vessel. As a result, liquid hydrogen is considered a strong candidate for export. However, liquid hydrogen faces the inherent issue of losses due to boil-off caused by external ambient heat, and significant energy cost in the liquefaction process.
- **Underground storage** – Underground caverns allow large-scale seasonal hydrogen storage; however, limitations exist in terms of geographic location and cavern porosity suitability for hydrogen.
- **Gas pipelines** – Storage in pipelines is useful for transport of hydrogen, but in most cases, this will require blending with methane gas and may be limited by pipeline compatibility with hydrogen. Further detail of hydrogen blending in pipelines is available in gas networks.

Figure 27: Compression and liquefaction storage technologies



RD&D priorities

RD&D PRIORITY AREAS	FACTORS
Cost, efficiency and capacity	**Storage system design**
	• Test hydrogen compatibility with container materials (gas blending) • Reduce in boil-off (i.e. vaporization) rates (liquefaction: cryogenic tanks, cryo-compression) • Make improvements to: engineering, insulation, heat exchangers and coolants (liquefaction: cryogenic tanks, cryo-compression) • Develop and test new designs and materials of construction (e.g. insulating glass beads) for larger and better insulated storage tanks (liquefaction: cryogenic tanks, cryo-compression) • Conduct modelling to understand storage capability of different geological systems, including factors such as porosity (underground storage)
	Balance of plant
	• Develop higher efficiency compression technologies (all) • Develop cost-effective auxiliary components with high durability when exposed to hydrogen (valves, seals, sensors, etc.) (pipelines, underground storage)
Cross-cutting research fields	**Environmental**
	• Conduct modelling and testing to understand the potential impacts of fugitive hydrogen emissions in the atmosphere (all)
	Social licence and safety
	• Design measures to prevent ignition of stored or leaked hydrogen (all) • Develop hydrogen sensors to detect leaks from caverns and reservoirs; in pipelines; and in commercial and residential contexts (pipelines, underground storage)
	Modelling
	• Conduct geological assessment and feasibility studies (underground storage) • Model cost-effective seasonal storage mechanisms and associated necessary storage system design features (all)

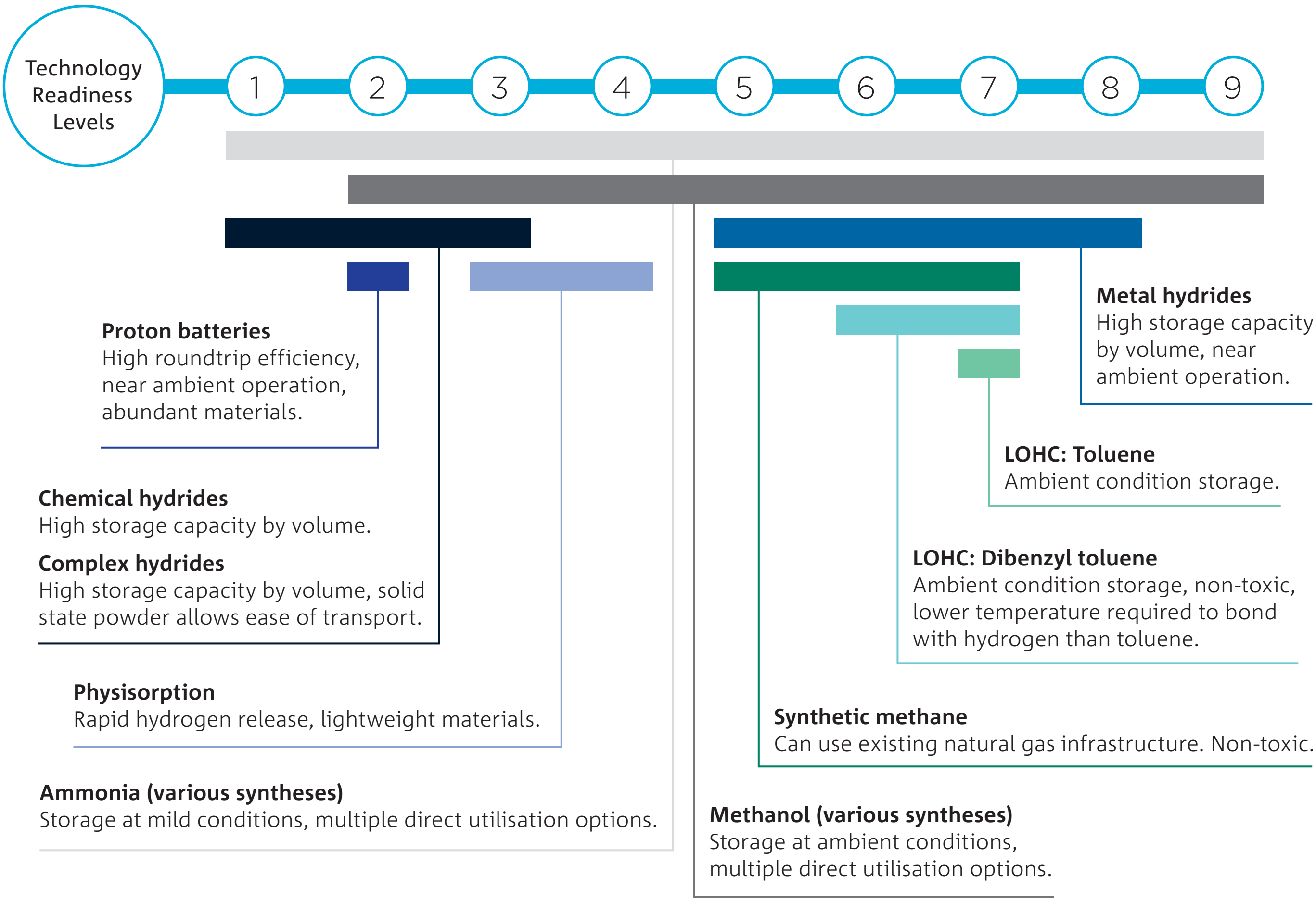
3.2.3 Chemical storage

Technology overview

In chemical storage, hydrogen is stored within a chemical or material, which acts as a hydrogen carrier for denser storage and transport. Hydrogen can later be extracted from the carrier for use. Hydrogen carriers yield the primary benefit of offering denser hydrogen storage at milder conditions than gaseous or liquid hydrogen. It is important to consider the energy costs to convert to and from hydrogen carriers, the rates of hydrogen loss during storage and distribution; and the ability to replenish a carrier for hydrogen storage reuse. These factors impact the overall efficiency of a given distribution option, and the costs associated with carrier lifetimes.

- **Ammonia** – Hydrogen is reacted with nitrogen, conventionally in the Haber-Bosch process, to synthesise ammonia. Ammonia has a high hydrogen density and can be stored and transported as a liquid under mild temperatures and pressures. Ammonia can then be converted back into hydrogen and nitrogen when required or utilised directly in various applications. A range of alternative synthesis routes for ammonia are currently being developed which could yield major improvements to energy efficiency and cost. Some routes also allow the direct synthesis of ammonia from nitrogen and water, without requiring the typical precursor hydrogen production step.
- **Synthetic fuels** – Hydrogen is reacted with another feedstock to generate a lightweight carrier (methanol, methane, or dimethyl ether) which has a high energy content. The synthetic pathways for these carriers are typically already well-established. These carriers offer greater gravimetric density than liquid organic hydrogen carriers, however require higher pressure or lower temperature conditions to store and transport as liquids with high volumetric density. These synthetic fuel carriers could also be used directly in some fuel cells or other applications instead of being converted back into hydrogen for use (see Part 3.3.2), in which case the initial inputs of the system are released.
- **Liquid organic hydrogen carriers (LOHCs)** – Hydrogen is stored within an organic molecule to generate a liquid organic hydrogen carrier. Hydrogen can later be extracted, and the carrier returned to the production site for hydrogen storage re-use. These carriers are liquid at ambient temperatures and pressures, requiring minimal energy for long-term and long-distance storage and transport. However, high temperatures are required to hydrogenate the carrier and to extract the hydrogen for use. Additionally, once the hydrogen is extracted the remaining carrier molecule requires handling or needs to be returned for re-use, resulting in additional transportation costs.
- **Hydrides** – Hydrogen reacts with a metal, metal complex, or other chemical to form a hydride, which is typically a solid material. The hydrogen is split in the process. The hydrogen can be stored or extracted via the application of heat, varying on the hydride class. Hydrides have high volumetric hydrogen density, whereas gravimetric density varies widely between types, with improved densities expected in future generations.
- **Electrochemical storage in carbon-based materials (AKA proton batteries)** – An electric current is applied to split water into oxygen and hydrogen atoms, which then bond individually to a carbon surface. The hydrogen atoms can later be extracted and reacted with water to produce electricity when required. Note that in this case, hydrogen gas (H_2) is not formed (or split) during the process, resulting in a higher roundtrip energy efficiency due to involving fewer chemical conversions.
- **Physisorption** – Hydrogen gas adsorbs (binds without strong chemical bonding) to the surface of a material or within the pores of a material lattice (e.g. MOFs, carbon nanomaterials, zeolites). Physisorption allows high gravimetric hydrogen density at cryogenic temperatures (~-196°C).

Figure 28: Chemical storage technologies



RD&D priorities

RD&D PRIORITY AREAS	FACTORS
Cost, efficiency and capacity	**Storage system design** • Improve volumetric and gravimetric density (solid storage) • Improve cycle life (metal hydrides, complex hydrides, proton batteries, LOHC: DBT) • Develop and test catalysts for chemical synthesis (ammonia, methanol) for reduced costs as well as better integration with VRE and distributed applications, or storage and release at closer to ambient temperatures (metal hydrides, complex hydrides) • Optimise synthesis conditions (ammonia, LOHCs) • Achieve a cost competitive production rate for alternative synthesis pathways, and develop processes that are suitable for distributed and intermittent operation (ammonia) • Develop processes to efficiently extract hydrogen after transport (methanol, LOHCs, synthetic methane, hydrides) • Improve carrier chemical regeneration efficiency (chemical hydrides) • Demonstrate hydrogen release at mild reaction conditions (metal hydrides, complex hydrides, LOHC: DBT) • Understand reactions between electrolyte and carbon surfaces (proton batteries) • Increase current densities during charging and discharging (proton batteries) • Increase the surface area of adsorbent materials, in order to increase storage capacity (physisorption) • Investigate the effects of dopants, catalysts, and substitution to improve hydrogen uptake (physisorption) **Balance of plant** • Integrate carbon capture and utilisation into existing methane synthesis processes (synthetic methane) • Develop higher efficiency compression technologies (hydrides)
Cross-cutting research fields	**Environmental** • Design pathways or procedures for environmentally suitable treatment of materials (all) • Design measures to mitigate marine and other environmental exposure (toluene, methanol, ammonia) • Develop and test effective means of integrating carbon capture, utilisation and storage (CCUS) to achieve zero-to-low carbon emissions (liquid and gaseous carriers) • Conduct modelling and testing to understand the potential impacts of fugitive hydrogen emissions in the atmosphere (all) • Conduct modelling and testing to understand the potential impacts of fugitive ammonia emissions on the natural environmental nitrogen cycle (ammonia) **Social licence and safety** • Design measures to prevent carrier ignition (all) (liquid hydrogen, methane, methanol) • Design measures and process features to mitigate of human contact with chemicals (liquid hydrogen carriers) • Understand health and safety risks cause by particulate matter from solid materials (solid storage materials)

3.3 Hydrogen utilisation

Hydrogen utilisation RD&D should focus on supporting and lowering the cost of unique hydrogen application end-use requirements, developing new hydrogen utilisation technologies particularly in large scale industrial settings, and removing entire process steps through direct carrier utilisation.

3.3.1 Introduction

Hydrogen has a myriad of applications and potential utilisation cases (see Figure 1). Many of these applications and utilisations have been covered in other parts of this report, such as in the gas networks for combustion to produce heat (Part 2.2) and in industrial processes (Part 2.5). This part builds on previous sections by describing the possible direct utilisation of hydrogen carriers or the use of hydrogen and hydrogen carriers in electricity generation and internal combustion engines.

Hydrogen carriers can be used directly, i.e. before they are converted back to hydrogen, either through combustion or electrochemistry. Electricity generation will also be discussed as an application in terms of stationary (fuel cells and turbines) and mobile (fuel cells) electricity generation.

It should be noted that this section does not comprehensively cover all hydrogen and hydrogen carrier utilisation technologies. Further work could be conducted to cover this area in greater detail, including the variations of each technology which exist.

3.3.2 Direct use of carriers

Synthetic fuel hydrogen carriers can also be used directly, rather than requiring a conversion back to hydrogen for use. Using carriers directly saves energy costs, acts as a low-carbon option for use in mature technologies and in some cases can utilise existing infrastructure where hydrogen technologies currently cannot. They are also currently used as feedstocks, which means there is already an established market for them as well as distribution infrastructure. Different utilisation cases can be seen in Figure 29. To be low carbon, the synthesised fuels need to derive their carbon source sustainably, such as through carbon capture or biomass.

Figure 29: Direct use of hydrogen carriers

UTILISATION	METHANE (CH_4)	AMMONIA (NH_3)	METHANOL (CH_3OH)	DME[57] (CH_3OCH_3)	FORMIC ACID (CH_2O_2)
Gas network injection	Developed				
Transport fuel	Developed	Developing	Developed	Developed	
Fuel cell input	Developed	Developing	Developed	Developed	Developing
Feedstock	Developed	Developed	Developed	Developed	Developed
Electricity via combustion	Developed	Developing		Developed	

■ **Developed** ■ **Developing**

57 Azizi, Z., Rezaeimanesh, M., Tohidian, T., Rahimpour, M. (2014). *Dimethyl ether: A review of technologies and production challenges*. Chemical Engineering and Processing.

- **Methane** can be synthesised by combining clean hydrogen and carbon dioxide through the Sabatier process. Being the main component of natural gas, it can be distributed to customers through existing networks for combustion. It can also be utilised as a fuel by LNG trucks. Japanese ENE-FARMs use methane as an input, where it is reformed to deliver hydrogen to a fuel cell to produce heat and power for residents. It can also be used directly in high temperature fuel cells to produce electricity. Finally, it can be delivered to and combusted in turbines to produce electricity.
- **Ammonia** can currently be synthesised through the established Haber-Bosch process, with numerous new synthesis methods under development. Ammonia is increasingly seen as a viable low-carbon option for long haul transport, such as shipping, where it could be combusted to produce emission-free energy. It can be also used directly as an input into high temperature fuel cells for electricity production.[58] Ammonia is currently used as a feedstock for many chemicals, mainly fertiliser, as well as being used to produce precursors for many nitrogen containing compounds like explosives. Electricity generation is also under development through the combustion of ammonia and ammonia blends in turbines (Part 3.3.3). While beyond the scope of this project, emerging technologies are also being developed to synthesise ammonia directly from water, without requiring generation of hydrogen as an initial feedstock. This presents an opportunity to reduce energy costs from chemical conversions across the value chain, and for ammonia to be a strong enabler of many cross-sector applications.
- **Methanol** synthesis involves the hydrogenation of carbon monoxide. Methanol is used as a fuel for transport in internal combustion engines both in blends and in its pure form. It can also be used as an input to methanol fuel cells. Amongst other applications, methanol is used as a feedstock to produce formaldehyde (a precursor for numerous products like resins and plastics) and dimethyl ether (see below). Importantly, methanol must be synthesised using a low-carbon pathway (via renewable feedstocks or with incorporated CCUS) in order to be a CO_2 neutral carrier.
- **Dimethyl ether (DME)** can be synthesised indirectly from methanol or directly from syngas. It is a gas in ambient conditions and liquid at 6 bars of pressure. In its liquid form, DME can be used as a substitute for diesel, producing low CO and NOx emissions on combustion. DME has also shown it can be combusted in a turbine to produce electricity, or used as a fuel cell input. DME can also be used as an aerosol, a coolant as well as an LPG substitute for combustion to produce heat. Importantly, DME must be synthesised using a low-carbon pathway (via renewable feedstocks or with incorporated CCUS) in order to be a CO_2 neutral carrier.
- **Formic acid** is conventionally synthesised via a two-step conversion of methanol, however newer approaches are emerging, such as CO_2 reduction, CO_2 hydrogenation, and oxidation of biomass. It is a liquid at ambient temperature and pressure, and has a high hydrogen content by volume. Formic acid can be used as a fuel in formic acid fuel cells and is also commonly used as a building block for subsequent chemical synthesis.[59]

58 Giddey, S., Badwal, S., Munnings, C., Dolan, M. (2017). *Ammonia as a Renewable Energy Transportation Media*. ACS Sustainable Chem. Eng. 2017, 5, 11, 10231-10239.

59 Rego de Vasconcelos, B., & Lavoie, J. M. (2019). *Recent Advances in Power-to-X Technology for the Production of Fuels and Chemicals*. Frontiers in chemistry, 7, 392. doi:10.3389/fchem.2019.00392

3.3.3 Electricity generation and internal combustion engines

Technology overview

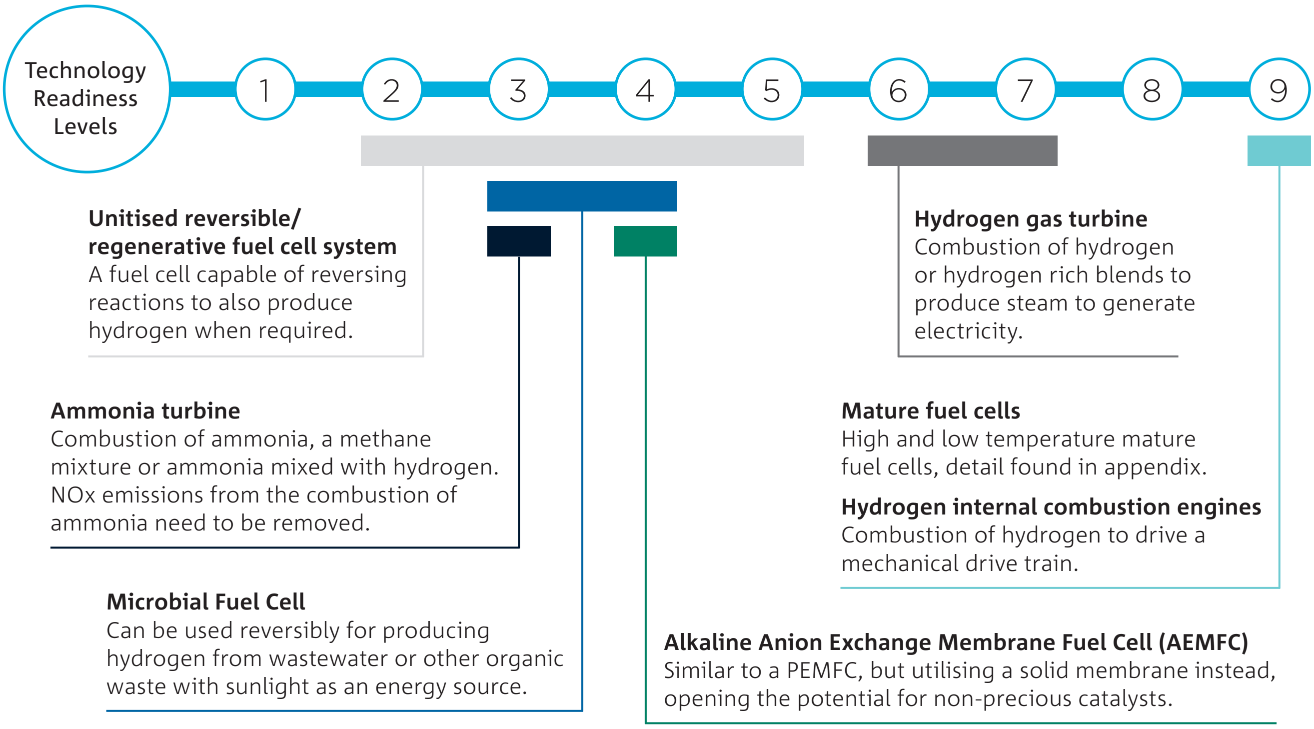
Hydrogen can be combined with oxygen in electrochemical processes or combusted in turbines to produce electricity; or combusted in internal combustion engines (ICEs) to produce heat energy and mechanical work for vehicles. Hydrogen's ability to be stored for long periods of time means it can be consumed for peaking or back up electricity generation services, at small or large scale. As mentioned (Figure 29), select hydrogen carriers can also be used directly in this manner to generate electricity and other forms of energy.

- **Fuel cells** are electrochemical cells that combine hydrogen (or hydrogen carrier) and oxygen to produce electrical energy (and combined heat energy that must be used or dissipated), as well as water as a by-product. The hydrogen source can vary, from pure hydrogen to methane or ammonia. There are range of fuel cell technologies with varying system sizes (kW to MW), chemical processes, operating temperatures, technological maturity, inputs and outputs; thus, different fuel cell technologies will have different ideal applications. They can be split into high and low temperature fuel cells, which changes the input allowance and general use case. High temperature fuel cells can accept a wider range of fuels and are usually used for stationary power, whereas low temperature fuel cells require pure inputs, and are more suited to small scale applications like mobility. Smaller fuel cell technologies can be utilised for stationary power in remote area power systems as well as mobile power (i.e. fuel cell electric vehicles like cars and trains). Fuel cells also make it possible to scale up to fulfil increasing energy demands, such as large trucks, trains or marine transport needs. A more detailed look at fuel cells can be found in Technical Repository.
- **Turbines** can produce electricity through the combustion of hydrogen or hydrogen-rich gases (such as hydrogen blended with natural gas or ammonia). Gas turbines burn a fuel, commonly natural gas but potentially hydrogen, ammonia, or blends thereof, to generate electricity as the expansion of the combustion gas spins a generator. By recovering the heat from the gas turbine to raise steam and run a steam turbine, additional generation (and therefore efficiency gains) can be achieved. By increasing the hydrogen content of a turbine, operators can incrementally shift to hydrogen as a fuel. Turbines that can burn higher hydrogen blends are increasingly being developed and tested, with a demonstrated cofiring of coal mixed with 20% ammonia in 2018;[60] and many companies pursuing 100% hydrogen capable turbines.
- **Internal combustion engines** produce heat and mechanical energy for vehicles. Although hydrogen presents challenges as a fuel, ICE technology has been demonstrated for hydrogen, with bolt-on modifications being made to conventional diesel or spark ignition ICEs to operate with gaseous hydrogen. This is usually port or direct injected in a similar manner to natural gas. For diesel engines a small amount of diesel fuel would be used to provide the ignition source. Some ICEs have been made to be dual-fuelled, being able to utilise petrol or hydrogen.[61] Compared to fossil fuel ICEs, the exhaust emissions from hydrogen engines produce no pollutants such as CO_2 or CO, and comparatively little NOx. Hydrogen ICEs face similar onboard storage challenges to FCEVs, which is exacerbated by the lower efficiencies of hydrogen ICEs. However, ICE technology continues to improve, with efficiencies of around 50% being achieved for automotive scale engines, and with further significant improvements likely. Overall, ICE technology is extremely flexible and reliable, and does not face the same challenges presented by FCEVs such as expensive catalysts that can be degraded by impurities in hydrogen supply.

60 IHI (2018). *Demonstration of the world's highest level of ammonia co-firing with a combustion test facility for coal-fired power plants -Contributing to CO_2 emission reduction-Development of combustion technology that enables the use of ammonia fuel* (English translation), [Online] Available from: https://www.ihi.co.jp/ihi/all_news/2017/technology/2018-3-28/index.html Accessed: 18/11/2019

61 Das, L.M. (2016). *Hydrogen-fuelled internal combustion engines*. Vol. 3, pp. 177-217. Compendium of Hydrogen Energy

Figure 30: Emerging hydrogen fueled electricity generation technologies



RD&D priorities

The RD&D priorities for fuel cells, turbines, and internal combustion engines are described below. Fuel cells are in effect the reverse of an electrolyser. Therefore, their components and processes are similar to electrolysers, resulting in similar RD&D needs. The US Department of Energy has set out clear technical goals for their fuel cell program, some of which are incorporated below.[62]

RD&D PRIORITY AREAS	FACTORS
Fuel cell cost and efficiency	**Stack design**
	• Minimise or eliminate precious metal use • Develop new materials and designs for electrolytes, catalysts, gas diffusion media and cell hardware • Improve management of water transport within cell • Develop membranes capable of higher temperature operation (up to 120 for PEMFC and above 120 for SOFC and molten carbonate FC) • Reduce cost and increase durability of membrane electrode assembly
	Balance of plant
	• Reduce cost and increase durability of BoP components including humidifiers, compressors and fuel processors
Turbine design[63]	**Durability and function**
	• Develop heat resistant materials to accommodate high temperatures associated with higher hydrogen blends • Design measures to reduce and manage combustion oscillation risk (oscillation can cause destruction of combustor) caused by higher flame speed • Reduce risk of flashback (backfire) in higher hydrogen mixes • Develop hydrogen ICEs to operate with blended or 100% gaseous hydrogen
Cross-cutting RD&D fields	**Safety**
	• Determine fuel cell stack failure mechanisms via experimentation
	Environment
	• Understand and manage emissions from ammonia and hydrogen turbines and engines

62 US Department of Energy (2017). *Multi-year Research, Development, and Demonstration Plan*, [Online] Available from: https://www.energy.gov/sites/prod/files/2017/05/f34/fcto_myrdd_fuel_cells.pdf

63 Mitsubishi Hitachi Power Systems (2018). *Insight of Large-scale hydrogen gas turbine Developer*, [Online] Available from: https://www.mhps.com/special/hydrogen/article_1/index.html Accessed: 18/11/2019

3.4 Cross-cutting RD&D fields

Cross-cutting RD&D in fields such as the environment, social licence and safety, policy and regulation, modelling and ancillary technology and services is required across the hydrogen value chain. When integrated, these fields can help achieve greater outcomes for industry, the community and the economy.

3.4.1 Introduction

The development of a hydrogen economy will not just be based on individual technologies or singular aspects of the value chain. There are numerous considerations that must be understood and RD&D activities that must be undertaken concurrently to ensure a state-of the-art, environmentally sound, socially responsible, commercially viable and adequately regulated hydrogen roll out.

Five cross-cutting RD&D fields have been identified through interviews and analysis (see Figure 31). In some cases, these RD&D fields are vital to project development and often have local or geographic parameters that require a research response tailored to Australia's unique circumstances. International examples should be borrowed, but not relied on, as Australia and its communities have unique needs that require ongoing consideration and engagement.

Each of the cross-cutting RD&D fields is required across the value chain and essential to addressing key hydrogen industry challenges.

- **Environment:** Research in land use, water use, atmospheric impacts and materials and waste management to inform industry strategy and specific project decisions;
- **Social licence, safety and standards:** Research to understand, engage and inform communities on the value, opportunities and risks associated with hydrogen; and ensure safe production, distribution and use of hydrogen;
- **Modelling:** Cutting edge scientific research drawing on existing and fundamental knowledge to inform decision making, reduce experiment time, provide insight to optimise systems and narrow technology selection;
- **Policy and regulation:** Research to support regulators and lawmakers during scale-up and the long-term development of the hydrogen industry;
- **Ancillary technology and services:** Research and technology development to create specialised hydrogen components for operations, streamline and integrate hydrogen technologies and processes, and maximise value from data across the value chain.

Importantly, these five areas are interrelated and can be integrated to achieve greater industry and economy-wide outcomes. For example, value and opportunities related to sector coupling can be enhanced through the combination of research efforts in land use and land rights, community engagement and modelling; and supported through the development of ancillary technologies that monitor and measure outcomes. Such combinations could lead to a more integrated approach to industry development, drive new opportunities and help to understand dividends for the entire economy. While this interrelationship could be a strength, silos across these RD&D fields can lead to duplication of effort and subpar outcomes.

Figure 31: Cross-cutting RD&D fields

3.4.2 Environmental

Environmental considerations are vital to any project. Assessments, planning, and considerations need to be included as part of any hydrogen technology implementation or demonstration project.

There have been many previous environmental assessments for other industries – implementors should draw learnings and existing expertise from these. However, there will be new risks and considerations that are specific to hydrogen at scale and in an Australian context which will need to be understood and acted upon.

CONSIDERATION	LAND USE AND ECOLOGICAL IMPACTS
Context	Land use and area requirements need to be considered for production facilities and supporting infrastructure. This is particularly important for large scale centralised hydrogen production facilities which could require significant renewable resources. There are also ecological implications to large scale land use such as soil structure degradation, interruption of natural water cycles, or impacts on flora and fauna species. Land use consideration also includes land rights, discussed further in policy and regulation (Part 3.4.5).
RD&D opportunities	• Review or design frameworks, tools and environmental assessments to help project proponents understand and incorporate land use considerations in hydrogen projects. This could include assessment and prediction tools to understand broader ecological implications from projects (including subsurface storage applications) or be related to specific environmental consideration such as the identification of measures to mitigate disruption of soil structure. • Conduct verification and monitoring to demonstrate ongoing integrity of local assets.

CONSIDERATION	WATER USE
Context	Many hydrogen production methods involve the conversion or reaction of water. The quality of water required can vary with some technologies, such as commercial electrolysers, allowing the use of low-grade potable water as an input. The quantity of water is highly dependent on hydrogen end-use requirements. For example, the total volume of water to support an Australian hydrogen export industry could be in the order of 5.6 GL to 28.6 GL per year by 2040.[64] While these volumes are far lower than in other large industries, they are not insignificant – especially for communities in regional areas. As such, sourcing sustainable quantities of water needs to be considered to produce hydrogen at scale. Importantly, appropriate mechanisms for pre-treatment of water and post-handling of waste streams (including salts and other residues) will be important to ensure minimal detriment to the environment.
RD&D opportunities	• Conduct water resource assessments and monitoring for sustainable water planning. This would be aided by improved data gathering technologies to improve characterisation and prediction of water resources. • Conduct economic and socio-economic modelling and analysis of water sensitivities associated with growth in the Australian hydrogen industry, alongside growth of other water dependent Australian industries and changes to water resources as a result of a changing climate. This may include consideration of ecological, Aboriginal cultural, social and tourism value from local water resources. • Adapt production technologies to use recycled, waste and mining water. This would need to consider different ions or contaminants that may be present at different sites. Alternatively, develop new technologies to clean water to a usable quality. • Conduct analysis and modelling of the techno-economic effects of desalinated water use. • Develop mechanisms to handle produced salt and recycle solids. • Trial reinjection of waste fluids (urban waste water, salty water, CO_2 from elsewhere) for pressure maintenance to ensure sustainability of water supply. • Improve measurement and monitoring technologies to measure water levels and quality. • Improve modelling to increase the accuracy of predictions associated with water use.

64 ACIL Allen Consulting for ARENA (2018). *Opportunities for Australia from hydrogen exports.*

CONSIDERATION	ACHIEVING ZERO-TO-LOW CARBON EMISSIONS
Context	While the long-term objective is for zero carbon emissions in hydrogen production, some hydrogen production methods produce carbon dioxide that needs to be managed, for example with carbon capture, utilisation and storage (CCUS). Beyond production it is also important to consider how best to achieve zero-to-low carbon emissions across the value chain. For example, there are also emissions associated with the establishment of infrastructure and some methods of hydrogen distribution (e.g. delivery of hydrogen via trucks). In order to achieve zero-to-low carbon emissions, procedures for capturing and storing or utilising carbon dioxide will need to be incorporated across the hydrogen value chain.
RD&D opportunities	• Conduct objective analysis on the most efficient way for Australia and the Australian hydrogen industry to grow with zero emissions production methods. This includes understanding how quickly zero-to-low emissions hydrogen production technologies could scale and would be needed to improve the pace of change. • Conduct global value chain and market analysis to understand short- and long-term Government and industry carbon risk drivers and demands. This could include analysis of strategies to overcome economic, legislative and higher-risk barriers in Australia. For example, issues related to project financing, incentives and the long-term liability of storing CO_2 underground. • Conduct life cycle analysis to understand carbon emissions across all stages of the value chain and identify areas where carbon emissions can be mitigated. • Contribute to development of associated regulatory standards for measuring and managing carbon emissions. • Demonstrate hydrogen production with integrated CCUS to ensure zero-to-low carbon emissions are achieved. • Reduce costs associated with carbon capture, utilisation, and storage. For example, reducing characterisation and monitoring and verification costs. • Identify new and alternative carbon utilisation technologies, dependent on the characteristics of the CO_2 stream (e.g. heat and volume). • Conduct studies to maximise storage capacity of matched sinks and expand the portfolio of suitable geology, including number and type of wells (horizontal vs vertical, multilevel completions).

CONSIDERATION	ATMOSPHERIC IMPACTS FROM FUGITIVE HYDROGEN AND AMMONIA EMISSIONS
Context	In addition to managing CO_2, the effects of fugitive hydrogen and ammonia emissions require examination. At this stage the effects are largely unknown, let alone on a large scale.
RD&D opportunities	• Measure and model the effects of fugitive hydrogen and ammonia emissions. For example, developing a greater understanding of local and regional air quality effects (and implications on human health) and global effects of an increase in utilisation of hydrogen and hydrogen carriers along with a decrease in consumption of fossil fuels.[65] • Conduct modelling to understand the potential impacts of fugitive ammonia emissions on nitrogen cycles in marine and other environments. For example, investigating any potential effects due to increases in atmospheric hydrogen on microbial communities in soils as hydrogen is used as a nutrient by soil bacteria. • Develop new materials to reduce fugitive emissions. • Develop sensors to detect and quantify fugitive emissions. Ideal sensors will be cost effective, reliable and robust. • Develop associated regulatory standards for measuring and mitigating fugitive hydrogen and ammonia emissions.

CONSIDERATION	MATERIALS AND WASTE MANAGEMENT
Context	Due to finite material availability and current global waste issues, material recyclability and the mitigation of unnecessary waste is important. Additionally, if large scale transport and export is realised, the risk of spills in marine and other environments must be mitigated.
RD&D opportunities	• Develop pathways and processes to handle and recycle materials for reuse. • Develop non-toxic substances and waste handling processes. • Conduct end-of-life asset management and decommissioning; explore strategies and recycling methods to minimise waste footprint.

65 CSIRO (2019). Hydrogen Energy Systems FSP – Triple Bottom Line, [Online] Available from: https://research.csiro.au/hydrogenfsp/home/triple-bottom-line/ Accessed: 18/11/2019

3.4.3 Social licence, safety and standards

Given the combustible nature of hydrogen, safe production, distribution and use is a priority. Demonstrating and communicating the outcomes of safe hydrogen projects is a vital step in building community support. Currently, there is a low level of public awareness about hydrogen which results in elevated perceptions of safety risks regarding accidents, collisions, fires and explosions.

CONSIDERATION	SAFETY AND STANDARDS
Context	Hydrogen is already used by large industries in Australia and overseas. As such, many industries have established safety standards, codes and practices associated with the production, storage and distribution and use of hydrogen. These approaches can be leveraged and applied to the variety of hydrogen end-use applications that are being developed. Caution should be taken given the different risk profiles of a well-managed and controlled industrial facility using hydrogen compared to hydrogen use in general public environments. As a hydrogen economy would involve hydrogen being used in different applications and sometimes different forms, further testing and studies may be required. The role of RD&D in safety will be informed by industry as their needs emerge and the RD&D ecosystem should to be ready and prepared to play that role. Importantly, any Australian RD&D activity related to hydrogen safety should be closely aligned to international efforts to avoid duplication of effort. For example, closely collaborating with or attending conferences related to Hydrogen Europe's Hydrogen Safety for Energy Applications (HySEA) project which is a consortium that aims to improve hydrogen safety through pre-normative research on vented deflagrations.[66]
RD&D opportunities	• Develop a greater understanding of auto-ignition challenges and risks. For example, understanding the correlation between pressure, leakage rate and leakage geometry. • Review international best practice safety standards to understand how Australian requirements can best leverage standards that exist or are under development. • Review and develop safety standards and approaches, particularly for emergency response, transport, and emerging hydrogen technologies that have not been deployed. These can be Australian specific if required but should seek to leverage international best practice. Share safety considerations in public engagement activities and communication materials.[67] • Develop or contribute to international safety knowledge repositories that promote shared lessons and help to rapidly improve global safety standards of the emerging hydrogen industry. • Develop hydrogen specific sensor technologies to detect and prevent safety risks (see Part 3.4.6). • Design measures to avoid hydrogen or hydrogen carrier leakage during transport or export. • Develop or gain experience in risk-based modelling tools and approaches to support industry development. For example, using Computational Fluid Dynamics (CFD) modelling tools to predict the release and dispersion of hydrogen with reasonable accuracy. • Review, understand and, where possible, help develop standards and guidelines related to handling of hydrogen and hydrogen carriers. From a hydrogen export perspective, this includes consideration of infrastructure development, loading and unloading at ports and shipping.

66 https://hydrogeneurope.eu/project/hysea

67 Lambert, V., & Ashworth, P. (2018). *The Australian public's perception of hydrogen for energy*, The University of Queensland, [Online] Available from: https://arena.gov.au/assets/2018/12/the-australian-publics-perception-of-hydrogen-for-energy.pdf

CONSIDERATION	SOCIAL LICENCE AND SOCIO-TECHNICAL RISK[68,69,70]
Context	Community engagement and social acceptance of small- and large-scale hydrogen projects and technology deployments is essential. It requires deep understanding of local stakeholders' expectations and an understanding of the challenges and needs that are of the greatest importance to local communities. RD&D is required to deliver empirically-based, trusted and clear explanations of the costs, risks and benefits associated with developing a hydrogen economy. RD&D can also help define and realise co-benefits from new hydrogen projects. There are opportunities to draw on lessons from established industries and apply them to a new hydrogen industry. It is anticipated that many new hydrogen development projects will be in regional areas and this will require fit-for-purpose engagement approaches.
RD&D opportunities	• Assess social attitudes towards hydrogen technologies and the role of hydrogen in energy systems to understand reputational risks and opportunities, influences on acceptance and behaviours on adoption. • Explore past lessons in effective communication and engagement, social acceptance and tolerance from similar large-scale energy technology domains. • Support communications and engagement activities with hydrogen project proponents to help build community support. This could include helping to optimise consultations and trials; developing and showcasing case studies; or co-designing tours, 3D demonstrations, interactive labs, and the integration of hydrogen into public infrastructure (e.g. fuel cell buses or trains). • Co-develop and deliver transparent community engagement strategies and understandable communication materials (using non-technical language) relaying messages about why hydrogen, associated benefits, costs and risks in partnerships with key stakeholders and communities. • Facilitate communities of practice across hydrogen communities to share learnings and implement a reflexive approach to engagement and deployment of projects.

CONSIDERATION	INDIGENOUS COMMUNITY AND TRADITIONAL OWNERS
Context	Development of Australia's hydrogen industry presents a significant opportunity for Australia's Indigenous community to be central to the energy transition. Rather than just being stakeholders that sign off on land use agreements under the Native Title framework, Traditional Owners and Indigenous communities have significant, long-term economic opportunities. However, they require the right information to drive these opportunities. Alongside the RD&D that is required to gain general community engagement and social acceptance (discussed above), further research is required to ensure that Indigenous communities are involved in and benefit from the expansion of the hydrogen industry on their country.
RD&D opportunities	• Engage with Indigenous Traditional Owners to understand and drive long-term opportunities for the community and region. This includes considering how hydrogen projects can support non-hydrogen related opportunities. For example, analysis that considers sector coupling, the circular economy or uses a longitudinal approach. • Explore the unique impacts and characteristics that expansion of the hydrogen industry on Indigenous lands could have (distinct from extractive and the broader renewables industry). • Provide the Indigenous community with information on the hydrogen industry and a clear articulation of the industry's expected impact to lands. • Engage with Indigenous Traditional Owners and industry to build appropriate guiding principles for access and benefit sharing agreements.

68 Ashworth, P. (2016) *Best Practice for Community Engagement: Determining Who is Affected and What is at Stake*. Available at https://www.cambridge.org/core/services/aop-cambridge-core/content/view/F47ADFF4BE4570D3986A4626DB5A7BB2/9781316341209c19_p391-410_CBO.pdf/best_practice_for_community_engagement_determining_who_is_affected_and_what_is_at_stake.pdf

69 Carr-Cornish, S., Lamb, K., Rodriquez, M., Gardner, J. (2019). *Social science for a hydrogen energy future*. CSIRO, Australia.

70 Hall, N., Lacey, J., Carr-Cornish, S., Dowd, A.M. (2015). *Social licence to operate: understanding how a concept has been translated into practice in energy industries*. Journal of Cleaner Production 86, 301–310.

3.4.4 Modelling

Computational modelling is a tool that is used to study the behaviour of different systems through computer simulations. It can range from studying molecular level attributes to analysis of the entire hydrogen value chain and should be performed prior to demonstration projects or experiments. Modelling can aid and accelerate decision making, reduce project uncertainties and complexities, provide insight to optimise systems and integration, narrow technology selection and demonstrate and determine project value and returns.

CONSIDERATION	MODELLING
Context	Different challenges will require different granularities of modelling. Modelling can be applied to help overcome various challenges across the hydrogen value chain from the molecular level though to the value chain integration.
RD&D opportunities	**Molecular:** • Materials modelling and simulations to reduce material selection and characterisation times. E.g. materials modelling to accelerate catalyst design. • Chemical and process reaction modelling to analyse reaction behaviours can optimise reaction efficiencies. **Device-level:** • Computational device modelling can aid device design by calculating optimal metrics. E.g. voltages, current density, gas circulation, water management.[71] **Value chain integration:** • Modelling can aid in optimising technology selections across production, storage and distribution to suit individual hydrogen use cases and scenarios. • Modelling can aid with understanding and connecting value chains elements in order to optimise sector coupling and design closed-loop systems **Geographical:** • Modelling can assist with analysing how geographical features and characteristics will inform the best technology choices (e.g. how do solar radiance, wind speeds, water availability, proximity to ports and other energy sources influence technology choice?). • Modelling of community perspectives to inform understanding of the social licence of companies and industries.[72] **Techno-economic:** • Techno-economic modelling of value chain configurations can narrow technology options to make better informed project finance decisions. • Techno-economic modelling of scaling efficiencies and cost barriers can inform decision making. • Modelling of future energy demand and markets, including consideration of regulatory and geopolitical barriers to international hydrogen trade, as well as competition with other energy export routes (e.g. HVDC cable electricity export). **Environmental:** • Environmental modelling can help assess the impact on carbon emissions if varying levels of clean hydrogen is introduced (e.g. injection into pipelines or clean hydrogen substituted into industrial processes). In many cases, such modelling requires fundamental scientific knowledge about the potential environmental effects of hydrogen (see Part 3.4.2).

71 Wetton, B (2016). *Mathematical Modelling of Electrochemical Systems*, Mathematics Applications Consortium for Science and Industry Workshop, [Online] Available from: https://www.math.ubc.ca/~wetton/papers/limerick16.pdf

72 Moffat, K., Lacey, J., Boughen, N., Carr-Cornish, S., Rodriguez, M. (2018). *Chapter 3: Understanding the social acceptance of mining*. In: Lodhia S (ed.) Mining and Sustainable Development: Current Issues. Oxon: Routledge, pp. 27–44.

3.4.5 Policy and regulation

Policy and regulation will largely be the domain of policy and law makers. The RD&D community can support the effective development of policy and regulation by remaining informed, responsive and ready to lend expertise as the industry develops. It is important to note that *Australia's National Hydrogen Strategy* has recommendations that align with many of the opportunities highlighted in this section.[73]

CONSIDERATION	POLICY AND REGULATION
Context	As the hydrogen industry is still developing and will cross numerous sectors, policy and regulation will continue to be reviewed and developed with a view to strike a balance that ensure planning, safety, installation and operation can occur without undue legal burdens.
RD&D opportunities	• Support the review of existing policies and regulations to identify root causes of legal and administrative barriers. Europe has undertaken this exercise and provides a good example through its HyLAW program.[74,75] • Following review, support the development of regulations specific to Australia's unique circumstances, with an objective of being proactive rather than reactive. • Study regulatory hurdles and ramifications of integrating and incorporating hydrogen production with the electricity sector, especially at scale. • Identify internal and external regulatory barriers to efficient international hydrogen trade and investment. This includes understanding how to best minimise exposure to political risk as well as understanding requirements to stimulate long-term technology investment. • Support the review and development of regulations needed specifically for safe storage of hydrogen including underground storage, and different methods of transportation (e.g. use of metal hydrides or ammonia).

CONSIDERATION	LAND RIGHTS
Context	In addition to land use (discussed in Part 3.4.1), land rights and area requirements need to be considered for production facilities and supporting infrastructure. This is particularly important for large scale centralised hydrogen production facilities which could require vast renewable resources on land over which Indigenous traditional owners have rights and interests, and which may contain important cultural sites in a cultural landscape. Native title and land rights legislation sets out ways in which project proponents can come to agreements over land use with traditional owners. While relevant legislation sets out the minimum standards that have to be met, it is accepted that 'best practice' agreement making must go above these legislative minimums to achieve a 'social licence to operate'. The process for achieving this engagement can be guided through direct interaction with regional land councils and native title representative bodies who can assist land owning groups in obtaining independent legal, scientific and business advice. Cultural heritage legislation must also be considered and complied with.
RD&D opportunities	• Support the development of information for hydrogen project proponents to legally and ethically engage with Indigenous land owners and representative bodies. • Support the development of information for policymakers, encouraging policy proven to capture benefit for Aboriginal and Torres Strait Islander people. • Develop hydrogen specific programs and public education campaigns to assist the general public, including Aboriginal and Torres Strait Islander people, understand the emerging hydrogen industry and land use specific considerations.

73 Commonwealth of Australia (2019) Australia's National Hydrogen Strategy. [Online] Available from: https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf, Accessed: 25/11/2019

74 European Commission - Community Research and Development Information Service (CORDIS) (2019). *Identifying legal and administrative barriers and solutions for hydrogen technology*. [Online] Available from: https://cordis.europa.eu/project/rcn/207656/brief/en?WT_mc_id=exp Accessed: 18/11/2019

75 HyLAW (2019). *HyLAW Online Database*, [Online] Available from: https://www.hylaw.eu/ Accessed: 18/11/2019

CONSIDERATION	GUARANTEES OF ORIGIN
Context	Countries importing hydrogen are doing so in order to decarbonise. Therefore, they will require assurances that the commodity is derived from clean methods. Guarantees of origin or hydrogen accreditation schemes will play a key role in defining renewable hydrogen and will support social acceptance in the hydrogen being used.
RD&D opportunities	• Support the development of clear and internationally accepted hydrogen classifications to support guarantees of origin or hydrogen accreditation schemes. • Identify best practice and inform metrics and measures that could be applied across the hydrogen value chain and used in any guarantee or origin or accreditation scheme that is developed. • Analyse long-term global demand side certification requirements and understand industry and government carbon risk profiles. • Inform or develop processes to verify provenance of clean hydrogen to assist in guaranteeing origin. • Identify opportunities to incentivise supply and demand side participation in and support for hydrogen guarantees of origin or accreditation schemes. • Develop technologies and sensors that would help collect valuable data to support guarantees of origin efforts (See Part 3.4.6).

3.4.6 Ancillary technology and services

Australia has many strengths in advanced manufacturing, technology and services, especially with regards to technology integration and process improvement. Australian manufacturers also have a strong reputation for quality, safety and reliability.[76] These strengths can be leveraged to develop specialised hydrogen components such as sensors and separation technologies; and to streamline and integrate hydrogen processes, such as hydrogen compression, liquefaction, or conversion. In addition to creating technology and service export opportunities, the development of these ancillary technology and service areas can lead to local capability that can be leveraged in projects.

CONSIDERATION	SEPARATION MATERIALS AND OTHER COMPONENTS
Context	Membranes and other separation materials and technologies are used in many processes and technologies across the hydrogen value chain. For example, the separation of hydrogen from a given hydrogen carrier or the separation of hydrogen from blended gas for different residential, commercial and industrial customers. Beyond separation materials is a broader need to develop specialised components and hydrogen compatible materials for use across the value chain. These include but are not limited to storage vessels, valves and fittings. While there are specific requirements and RD&D needs for each technology, all can leverage developments in advanced manufacturing and material sciences to improve outcomes.
RD&D opportunities	• Improve the testing, development and assembly of separation technologies and reduce manufacturing costs and production times. • Develop technologies that allow for sensors and other monitoring devices to be embedded in or linked closely to membranes and other separation technologies. • Identify and develop hydrogen compatible materials that can be applied in multiple components and applications and be used across the value chain.

76 CSIRO Futures (2016). *Advanced Manufacturing – A Roadmap for unlocking future growth opportunities for Australia.*

CONSIDERATION	SPECIALISED SENSORS, MONITORING DEVICES AND OTHER COMPONENTS
Context	There are opportunities for the hydrogen industry to employ state-of-the-art advanced manufacturing and digital technologies to develop specialised sensors, monitoring devices and other components for use across the hydrogen value chain. For example, the development of sensors that can help provide transparency across the value chain and support hydrogen provenance activities or improve safety.
RD&D opportunities	• Utilise monitoring technologies to support hydrogen production by obtaining data on pressure, temperature, flow rates and other variables, allowing for real-time decision-making. • Improve sensors via developments across characteristics such as: sensor durability, sensitivity, parameters, capacity, size, energy requirements, maintenance requirements. • Deploy data sciences, cyber security and analytics solutions to support decision making and improve how operational information across the hydrogen value chain is stored, managed and used.

CONSIDERATION	TECHNOLOGY INTEGRATION AND PROCESS IMPROVEMENT
Context	Global hydrogen RD&D will result in many new technologies and processes that can be adapted and integrated into Australian operations. Integration of technologies such as energy sources, production and storage systems will require considerable effort and iterative testing to optimise efficiency. Australia has a noted strength in this area, with many businesses specialised in modifying and adapting innovations developed by other parties.[77]
RD&D opportunities	• Integrate and optimise of off-the-shelf products into hydrogen processes to achieve efficient whole-system operation. • Automate technologies and robotics to optimise manufacturing operations and processes, improving overall productivity through systems integration. • Develop systems integration software to ensure equipment and technologies work together seamlessly; and to optimise systems for maximum operational performance. • Develop remote operations technologies to improve safety of workers and allow for monitoring asset integrity, predicting risks and preventing incidents. • Package production, storage and utilisation technologies to provide a suite that is optimised for a given end use or context (industrial, residential, or remote).

77 Department of Industry, Innovation and Science (2019). *Australian Innovation System Monitor*, [Online] Available from: https://publications.industry.gov.au/publications/australianinnovationsystemmonitor/business-innovation/innovation-activity/index.html

4 Enhancing Australian hydrogen RD&D outcomes

Mobilising the RD&D community to address hydrogen industry development challenges requires coordinated actions from across the research community, industry and government

While there is no silver bullet to enhancing Hydrogen RD&D outcomes in Australia, based on interviews and analysis this report has identified four interrelated themes with specific actions that could be taken. Many of the themes and actions identified are related to recommendations within *Australia's National Hydrogen Strategy.*[78] For example, the international collaboration theme which could be supported by actions related to international agreements within the Strategy.

These themes are not unique to hydrogen RD&D and in many cases apply equally to Australia's national innovation system. Therefore, any effort to enhance Australia's hydrogen RD&D outcomes can also be leveraged to support improvements in Australian innovation and RD&D more broadly

RD&D strategy: Establish and monitor ongoing RD&D priorities for Australia as part of national hydrogen industry strategy. Activities should focus on encouraging hydrogen RD&D collaboration, identifying ongoing RD&D opportunities and reporting on progress. This monitoring should be linked to other monitoring of hydrogen industry development as identified by A*ustralia's National Hydrogen Strategy*.

Industry scale-up: Enable hydrogen industry growth through hydrogen hubs that support scale-up and establish pathways for greater RD&D engagement and technology development.

International collaboration: Establish joint programs with international Governments and industry to facilitate RD&D connections and contributions to international hydrogen RD&D efforts, with a focus on supporting timely global and domestic hydrogen industry development.

Culture and capability: Build collaborative hydrogen industry-research sector interactions through engagement programs and activities which unite industry and RD&D communities in identifying and addressing key industry challenges.

4.1 RD&D strategy

As both the domestic and global hydrogen industry grow, it is anticipated that Australia's RD&D opportunities and priorities will evolve over time. Keeping track of these evolving RD&D opportunities and priorities will require a coordinated and ongoing strategic review and response. This will be key to realising the economic gains available from the hydrogen industry and maximising the value of Australia's RD&D contribution to it.

Proposed action:

Establish and monitor ongoing RD&D priorities for Australia as part of national hydrogen industry strategy. Activities should focus on encouraging hydrogen RD&D collaboration, identifying ongoing rd&d opportunities and reporting on progress. This monitoring should be linked to other monitoring of hydrogen industry development as identified by *Australia's National Hydrogen Strategy*.

The insights from this report provide the foundations for a hydrogen RD&D strategy and the identification of Australian RD&D priorities. However, there is a need for further work to occur. This includes continuing to develop and optimise this analysis, establishing mechanisms that support RD&D investment, championing RD&D activities and supporting knowledge sharing across the broader innovation ecosystem.

78 Commonwealth of Australia (2019) *Australia's National Hydrogen Strategy.* [Online] Available from: https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf, Accessed: 25/11/2019

Key activities to support the ongoing establishment and monitoring of RD&D priorities could include:

- **Identifying and supporting a prioritised and balanced portfolio of hydrogen RD&D opportunities that considers both industry-driven and fundamental RD&D:** A centralised body could act as an overseer of opportunities to ensure a diverse selection of technologies and cross-cutting research areas are pursued. A comprehensive oversight of Australia's hydrogen RD&D would allow the body to:
  - minimise duplication of effort across the country;
  - raise awareness of RD&D investment opportunities for industry;
  - ensure support and attention is given to both industry-driven and fundamental RD&D (given its potential to yield long-term step-changes);
  - act as a collection point for industry's perspectives and needs;
  - continue to champion hydrogen RD&D opportunities as they develop to ensure continued support; and
  - continue to monitor RD&D progress to ensure lessons learned are integrated into ongoing efforts.
- **Providing support for projects to have early access to modelling and techno-economic analysis:** Access to this type of analysis could help projects identify specific cost targets or industry outcomes that RD&D should aim to achieve. For example, while the CSIRO National Hydrogen Roadmap did not model RD&D outcomes directly, the industry driven techno-economic modelling identified sensitivities and key technology cost drivers that can help direct further effort or investment. If shared, this analysis could support broader industry and technology knowledge sharing needs (discussed below).
- **Establishing knowledge sharing mechanisms to accelerate industry innovation and enable industry-RD&D collaboration:** This could include the development and maintenance of a repository of both domestic and international hydrogen industry and RD&D projects. Such a repository would help avoid duplication of effort and ensure that local and global best practice is being leveraged and applied. There are several international hydrogen platforms that have online repositories that could be leveraged (see Part 4.3: International Collaboration). Where possible, knowledge sharing mechanisms should seek to define mutually agreed levels of transparency to allow researchers visibility of industry requirements, help establish and direct industry co-investment, and ensure that findings are adequately being translated to de-risk the industry.
- **Establish RD&D KPIs that support hydrogen innovation:** Key performance indicators (KPIs) can be used to support innovation and encourage emergent RD&D and greater activities beyond publications or grant outcomes. Where possible, KPIs should aim to be hydrogen-specific; for example, tracking Australian patent filings across the value chain or collecting data on joint hydrogen projects with industry (start-ups, small to medium-sized enterprises, and large organisations). However, KPIs should also consider a balanced portfolio approach. This includes the exploratory nature of emergent research, which does not always – and is not intended to – result in immediate commercial outcomes. Importantly, the KPIs identified should aim to be aligned with the findings from the Australian Innovation Metrics Review expected in late 2019.[79]

79 Department of Industry, Innovation and Science (2019). *Innovation Metrics Review*, [Online] Available from: https://www.industry.gov.au/data-and-publications/innovation-metrics-review Accessed: 18/11/2019

4.2 Industry scale-up

There is a global need for commercial-scale investments which demonstrate the viability and cost-competitiveness of hydrogen industry pathways. Supporting this scale-up will require concerted and collaborative action from industry, government and communities, with RD&D acting as a critical enabler. However, a long-term risk for Australia's hydrogen industry could be created if there is a lack of domestic collaboration and coordination.

Proposed action:

Enable industry growth through hydrogen hubs that support scale-up and establish pathways for greater RD&D engagement and technology development.

The creation of hydrogen hubs has been identified by the National Hydrogen Strategy as key to supporting industry development by making infrastructure more economic, allowing for efficiencies from scale, fostering innovation, facilitating the sharing of expertise and services and promoting sector-coupling.[80] This finding is aligned with international analysis. For example, the recent IEA hydrogen report[81] highlighted the value of hubs and industrial clusters to support hydrogen industry growth and members from Mission Innovation's Innovation Challenge 8: Renewable and Clean Hydrogen (IC8) developed the concept of Hydrogen Valleys.[82]

Most importantly for the RD&D community, the establishment of relevant hubs would help bring together industry stakeholders and support engagement; provide clearer direction on demonstration and scale-up requirements; and help maintain focussed effort and a long-term perspective. To be successful, this approach would require substantive guidance at a national level to see beyond immediate interests in order to capture the long-term RD&D opportunities and provide the greatest future benefit.

Key activities to support the hydrogen hubs include:

- **Providing incentives for industry, technology providers and researchers to collaborate and de-risk technologies within hubs and demonstrators:** Moving RD&D opportunities from a lab or small-scale environment (e.g. TRL4-5) to a larger scale pilot or commercially viable solution (TRL6-8) is challenging. It requires significant investment and close collaboration between industry, technology providers and the RD&D community as project complexity, engineering and funding requirements can change considerably. For example, as scale increases the facility would require larger power supplies, greater safety measures and consideration of hydrogen offtakes. Hydrogen hubs and demonstrators can provide such scale and allow industry and the RD&D community to consider integration, safety and the testing of emerging and mature technologies side by side. They can also reduce or help share the cost of entry. However, all parties would require financial and non-financial incentives for such collaborations to occur. These incentives would need to consider risks and rewards for such collaborations, objectives of technology and equipment providers operating within a hub, and processes to support collaboration, such as procedures for IP protection.
- **Promoting early collaboration and engagement activities between researchers and engineers through RD&D scoping studies:** Scale-up of emerging technologies will be strengthened and potentially accelerated through greater knowledge sharing and collaboration between researchers and engineers. Such activities could be achieved through investment in scoping studies for RD&D projects and demonstrations to validate opportunities ahead of conducting a hydrogen project within or outside of a hub or demonstrator. Importantly, the different disciplines and perspectives can challenge each other to identify technical and non-technical targets, lessons or gaps in knowledge that could be addressed through the demonstrator or facility; test what is being proposed against global activities; help to understand the technology trajectory and commercial and social project considerations; identify engineering requirements for scaling; and develop high-level scaling cost estimations.

80 Commonwealth of Australia (2019) *Australia's National Hydrogen Strategy*. [Online] Available from: https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf, Accessed: 25/11/2019

81 International Energy Agency (2019). *The Future of Hydrogen: Seizing Today's Opportunities.*

82 Mission Innovation (2019). *"Hydrogen Valleys": demonstrating the power of hydrogen*, [Online] Available from: http://mission-innovation.net/2019/05/13/hydrogen-valleys-demonstrating-the-power-of-hydrogen/ Accessed: 18/11/2019

Beyond technological factors, such collaborations or scoping studies could also assist with community engagement and early consideration, accounting and mitigation of environmental impacts.

- **Supporting hydrogen RD&D projects with small to medium-sized enterprises and start-ups:** In addition to large national and multi-national organisations, the Australian and global hydrogen industry will be supported by solutions from small to medium-sized enterprises and start-ups. While some of the required solutions are known (see examples in Part 3.4.6), others will emerge as the technologies are deployed at scale and the hydrogen value chain is established. Working with the RD&D sector, these organisations can develop novel hydrogen value chain technologies, processes and services that could be utilised or sold domestically and in international markets. Establishing these relationships and projects takes work. Existing national and state-based funding and facilitation schemes are available to Australian small to medium-sized enterprises and start-ups that can be leveraged to support this action.
- **Supporting and streamlining access to new and existing hydrogen research facilities:** Any hydrogen research facility investments should be made as part of a broader investment plan. For example, a broader investment plan could take into consideration Australia's National Collaborative Research Infrastructure Strategy (NCRIS)[83] and global hydrogen research facilities (such as those accessed through international platforms like Mission Innovation).[84] This would help to understand where new infrastructure might be required, where Australia could choose to build strategic in-country capability, or where there may be opportunities to improve access to or time on existing national or international facilities.

4.3 International collaboration

International hydrogen RD&D collaboration is an opportunity for Australia. It can help to avoid unnecessary duplication of effort across collective global industry opportunities and challenges. It offers a more effective way to accelerate hydrogen technology development and adoption by leveraging existing capability, infrastructure and talent; pooling capital; and sharing risks and rewards. Finally, it can support international relationship building, using science (and science networks) as a vehicle for international diplomacy and strengthening Australia's bilateral relationships.

Findings from researcher interviews and analysis highlighted that international RD&D collaborations in hydrogen is currently often driven by chance and not connected to a broader national or industry strategy.

Proposed action:

Establish joint programs with international Governments and industry to facilitate RD&D connections and contributions to international hydrogen RD&D efforts, with a focus on supporting timely global and domestic hydrogen industry development.

While Australia has established international research funding schemes which call for multi-lateral partners, very few are hydrogen-specific, and challenges exist that limit the uptake and success of international RD&D collaborations. Successfully establishing joint programs with international organisations and governments requires deep understanding of international market drivers and the strategic goals of individual international proponents. When compared against Australia's priorities and RD&D capabilities, this understanding will help identify collaborations that will benefit both the target country and Australia. While analysis can help, many insights and opportunities will be gained by actively fostering international relationships.

83 Department of Education (2019). *National Collaborative Research Infrastructure Strategy (NCRIS)*, [Online] Available from: https://www.education.gov.au/national-collaborative-research-infrastructure-strategy-ncris Accessed: 18/11/2019

84 Mission Innovation (2019). *"Hydrogen Valleys": demonstrating the power of hydrogen*, [Online] Available from: http://mission-innovation.net/2019/05/13/hydrogen-valleys-demonstrating-the-power-of-hydrogen/ Accessed: 18/11/2019

Key activities to support the establishment of joint programs could include:

- **Enabling translation of international experience by supporting participation in international hydrogen collaboration platforms:** There are a variety of international platforms that manage hydrogen-specific events, knowledge repositories and funding programs (See Figure 32). Australia is already active in several of the international platforms mentioned, in particular: Mission Innovation, IEA TCP and IPHE. However, there are opportunities to increase Australian participation. An example of encouraging participation can be seen through ARENA's International Engagement Program, which provides grant funding to support Australian participation in international programs.[85] Another pathway to increasing participation is to work with existing collaboration platforms to host events in Australia. Federal, state and territory government trade and investment authorities can also play a key supporting role in international platforms - particularly as these agencies would have awareness and visibility of local activities and events that relate to but extend beyond hydrogen RD&D. For example, forums such as the Hydrogen Energy Ministerial Meeting 2019 being held by the Ministry of Economy, Trade and Industry (METI) and the New Energy and Industrial Technology Development Organization (NEDO) in Japan.[86]
- **Analysing drivers and strategic goals by country:** Analysis should seek to identify gaps and help determine where Australian RD&D capability could play a leadership role and be best suited to support an existing international project. Such analysis could also support a 'team Australia' approach that avoids duplication of effort and better coordinates engagement. This analysis should leverage and be informed by the Australian Trade and Investment Commission as well as Australian state and territory government trade and investment authorities. It should also leverage and build on existing resources such as the hydrogen partners activity in the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)[87] or the recent analysis from the Future Fuels CRC (see Figure 33).
- **Establishing an international hydrogen RD&D partnership scheme and bilateral agreements:** In addition to participating in international platforms, Australia may consider establishing a specific hydrogen RD&D partnership scheme or bilateral agreement that targets hydrogen technology development and knowledge sharing. The hydrogen RD&D scheme could be modelled on existing programs. For example, the Global Innovation Linkages and the Global Connections Fund through the Australian Department of Industry, Innovation and Science,[88] the Green Ammonia Consortium,[89] or the Linkage and Discovery Program offered through the Australian Research Council.[90] Alternatively, the scheme could focus on a country-to-country partnership. An example of this can be seen through the Energy Transition Hub, a collaborative venture supported by the Australian Department of Foreign Affairs and Trade and the German Federal Ministry of Education and Research.[91]

85 ARENA (n.d.). *International Engagement Program*, [Online] Available from: https://arena.gov.au/funding/international-engagement-program/ Accessed: 18/11/2019

86 Ministry of Economy, Trade and Industry (METI) (2019). *Hydrogen Energy Ministerial Meeting 2019 to be Held*, [Online] Available from: https://www.meti.go.jp/english/press/2019/0408_003.html Accessed: 18/11/2019

87 International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) (2019). *IPHE Partners*, [Online] Available from: https://www.iphe.net/partners Accessed: 18/11/2019

88 Department of Industry, Innovation and Science (2019). *International research collaboration*, [Online] Available from: https://www.industry.gov.au/funding-and-incentives/business-and-startups/international-research-collaboration Accessed: 18/11/2019

89 Muraki, S. (2018). *Development of Technologies to Utilize Green Ammonia in Energy Market*, [Online] Available from: http://nh3fuelassociation.org/wp-content/uploads/2018/11/AEA-Imp-Con-01Nov18-Shigeru-Muraki-Keynote-Address.pdf

90 Australian Research Council (2019). *Opportunities for international research collaboration*, [Online] Available from: https://www.arc.gov.au/policies-strategies/strategy/international/opportunities-international-research-collaboration Accessed: 18/11/2019

91 Energy Transition Hub (n.d.) *About*, [Online] Available from: https://www.energy-transition-hub.org/about Accessed: 18/11/2019

- **Providing international project engagement and execution support services:** Based on researcher interviews, miscommunication or misunderstanding of priorities, objectives, intellectual property (IP) ownership and the flow of money were cited as primary sources of many issues in collaborative projects that can be magnified in an international context. While there is no simple solution, access to support services or in-country expertise can be valuable. For example, IP and contractual arrangements are difficult in international collaborations and require appropriate legal advice. It is important to understand how countries perceive and handle IP, as each country has a different understanding of where IP comes into play when signing an agreement for a collaboration or potential collaboration. Lack of an effective arrangement can slow or stall a collaboration, or worse establish a collaboration that is ill-informed and does not adequately protect Australian IP.

Figure 32: International hydrogen collaboration platforms

The following is a selection of international hydrogen collaboration platforms:

- Mission Innovation[92]
- International Energy Agency (IEA) Hydrogen Technology Collaboration Programme (TCP)[93]
- International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)[94]
- International Association for Hydrogen Energy (IAHE)[95]
- Hydrogen Europe (European Hydrogen and Fuel Cell Association)[96]
- U.S. Department of Energy's (DOE's) Fuel Cell Technologies Office[97]
- Fuel Cells and Hydrogen Joint Undertaking (FCH JU)[98]

92 For more information: mission-innovation.net/our-work/innovation-challenges/
93 For more information: www.iea.org/tcp/hydrogen/
94 For more information: www.iphe.net/partners
95 For more information: www.iahe.org/
96 For more information: www.hydrogeneurope.eu/
97 For more information: www.energy.gov/eere/fuelcells/fuel-cell-technologies-office-key-activities
98 For more information: www.fch.europa.eu/page/who-we-are

Figure 33: Understanding international markets

A key resource to support Australia's understanding of international markets is the Future Fuels CRC's report titled Advancing Hydrogen: Learning from 19 plans to advance hydrogen from across the globe.[99] The report provides a comprehensive summary of national and regional strategies and industry roadmaps for the development of hydrogen and its derivatives. Its aim is to help all interested in the emerging hydrogen industry to understand what is happening elsewhere.

Building on the report's analysis, the figure below presents primary hydrogen end-uses described in country strategies and their alignment with the five Australian industry opportunities discussed in this report. With further work these insights can be leveraged to understand RD&D gaps and ultimately identify opportunities for international hydrogen RD&D collaborations.

	H_2 production for export	H_2 in gas networks	H_2 for industrial heat	H_2 for household heating	H_2 for heavy vehicles	H_2 for passenger vehicles	H_2 for electricity and combined heat/power gen.	H_2 for industrial feedstocks
Brunei	■							
China	■				■	■		
European Union		■	■	■	■		■	■
France					■			■
Germany		■		■			■	
Japan					■	■	■	
Netherlands		■		■				■
Norway	■				■	■		
Republic of Korea		■			■	■	■	
United Kingdom		■	■	■	■	■		
USA					■	■	■	

■ **Primary hydrogen end-uses inferred from the country strategies. Note: Highly simplified summary adapted from Kosturjak A, Dey T, Young M D, Whetton S (2019) Advancing Hydrogen: Learning from 19 plans to advance hydrogen from across the globe, Future Fuels CRC.**

99 Kosturjak, A., Dey, T., Young, M.D., Whetton, S. (2019). *Advancing Hydrogen: Learning from 19 plans to advance hydrogen from across the globe*, Future Fuels CRC.

4.4 Culture and capability

There are many individual researchers and institutions working in hydrogen that are already highly engaged with industry. However, it is not consistently occurring across the Australian hydrogen RD&D community. Based on interviews and analysis, many of the industry and research collaboration issues stem from differences in RD&D attitudes, drivers and objectives across innovation stakeholders. As highlighted in Part 1, this challenge is cultural and broader than hydrogen RD&D in Australia.

> **Proposed action:**
> Build collaborative hydrogen industry-research sector interactions through engagement programs and activities which unite industry and RD&D communities in identifying and addressing key industry challenges.

While there is no simple solution to improve collaboration outcomes for all Australian RD&D, addressing the challenge in the hydrogen industry is achievable given the nascent state of the industry and hydrogen RD&D. While new hydrogen-specific programs could be created, there are many well-established mechanisms that could be leveraged to improve business and research collaboration. For example, CRCs and other programs and funding mechanisms available through the Australian and State Government.[100]

Several researchers interviewed for this project had an appreciation that the research community itself often does not have a good understanding of industry challenges and does not always present research opportunities in a way that aligns to industry needs· Similarly, those in industry that were interviewed acknowledged that they need to improve how they engage with research, better understand how to frame industry challenges and look beyond a two-year horizon· As stated, this is a cultural challenge that can only be addressed through the development of relationships over time·

Key activities to help build collaborative hydrogen industry-research sector interactions could include:

- **Launching industry placement or secondment programs for researchers**: The Australia 2030 report highlighted Australia's lack of at-scale industry placement programs for higher degree research students. It goes on to cite the importance these programs have in building collaboration skills and improving the quality and quantity of researchers. Lessons can be learnt and applied from an exercise undertaken in 2017 where the Australian Government provided support to the Australian Mathematical Sciences Institute to place 1,400 PhD interns in industry by 2020's end.[101] Through these programs, host companies can support researchers in understanding and addressing the challenges faced in industry.

100 Department of Industry, Innovation and Science (2018). *How collaboration can help your business*, [Online] Available from: https://www.business.gov.au/change-and-growth/innovation/business-research-collaboration Accessed: 18/11/2019

101 Innovation and Science Australia (2017). *Australia 2030: prosperity through innovation*, Australian Government

102 ON Innovation (n.d.) *Hydrogen Heroes*, [Online] Available from: http://www.oninnovation.com.au/en/News/Hydrogen-Heroes Accessed: 18/11/2019

- **Running targeted hydrogen incubator or accelerator programs to encourage innovation:** These types of programs create a way for researchers to gain insights from industry in a structured and time-bound manner. They offer tools and a structured framework to help researchers with problem definition and research scoping; and enhance the RD&D community's ability to translate business objectives and priorities into appropriate research and development project questions (and vice versa). An example can be seen through the CSIRO ON Program, which had a biological hydrogen production team from Macquarie University participate in its ON Prime (pre-accelerator) program. Through the program and the industry consultations conducted, the team gained valuable insights into the requirements from industry when adopting new technology and substantially refined their value proposition which led to changes in their research direction.[102]
- **Enabling and recognising the value of Australian and international in-kind industry contributions to RD&D:** While industry funding is valuable and demonstrates project commitment, early stage projects (like fundamental research) can benefit greatly from industry input. For example, the input could support concept validation and identify constraints or requirements for upscaling a given technology (such as through engineering partners). In-kind contributions could also lead to greater buy-in and informed supporters once greater funding is required. It may require a mindset shift or reviews of funding and grant rules to ensure that they recognise the value of in-kind industry contributions and expertise. For partners like engineering firms that operate with a fee-for-service model, in-kind contributions may require a support mechanism for including sub-contracting where appropriate.
- **Continuing to grow a comprehensive hydrogen stakeholder network by supporting hydrogen-specific conferences and events:** This can be achieved by bringing researchers and industry (investors, developers, engineers and end-users) together to discuss progress and mutual challenges and align direction of future efforts. Although the last two years has seen the rate of hydrogen conferences increase, it is important to continue to drive the attendance of a diverse set of industry members and researchers, as well as ensure that networking is occurring across a range of topics. Furthermore, given the rapid growth of hydrogen activity, it is important to continue to build these networks and involve industry newcomers. In some cases, researcher attendance may need to be incentivised, keeping in mind travel requirements and admission costs.

5 Conclusion

International momentum towards the development of a clean hydrogen industry is building, with industry development quickly approaching an inflection point and beginning a period of rapid growth.

Critical to Australia securing its place in the global hydrogen opportunity and developing a world class industry is its collaborative, transdisciplinary and strategically aligned RD&D ecosystem.

There are many hydrogen industry growth opportunities for Australia, including development of a new hydrogen export industry, the use of hydrogen in gas networks, and for transport, electricity systems support and industrial processes. As the market develops further, there will be even more opportunities for Australia beyond those identified, especially for the nation's advanced manufacturing sector.

Australia's hydrogen opportunities, and the RD&D priorities to support them, will continue to evolve based on changes in national priorities, progress in global and domestic hydrogen projects, and other developments in Australia's hydrogen industry and RD&D capabilities.

Beyond supporting *Australia's National Hydrogen Strategy*, this report aims to spark a broader national discussion between industry, government and the research community about the role of RD&D and how it can be best leveraged now and into the future. To support this objective, individual parts of the report (and the Technical Repository[103]) have been designed as a framework that can be revisited and revised as the industry develops or as new information becomes available.

The scale of Australia's hydrogen opportunity is too large to be left to chance. While the nation has a well-positioned hydrogen RD&D community, successfully leveraging this to build a domestic industry and support market activation requires collaboration. Strategic, coordinated action is critical in realising the opportunities available through RD&D to facilitate the growth of Australia's emerging hydrogen industry.

103 Charnock, S., Temminghoff, M., Srinivasan, V., Burke, N., Munnings, C., Hartley, P. (2019). *Hydrogen Research, Development and Demonstration: Technical Repository*, CSIRO.

6 Appendix

Input for this report was sought from a broad range of stakeholders. This includes consultations with representatives from 35 industry and government organisations as well as approximately 80+ researchers from the following research institutions:

- The Australian National University
- The Blue Economy CRC
- CSIRO
- Curtin University
- Deakin University
- Flinders University
- The Future Fuels Cooperative Research Centre
- Griffith University
- Macquarie University
- Monash University
- Queensland University of Technology
- RMIT University
- Swinburne University
- The University of Adelaide
- The University of Melbourne
- The University of Newcastle
- The University of Queensland
- The University of Sydney
- The University of Technology Sydney
- The University of Western Australia
- The University of New South Wales
- Victoria University
- Western Sydney University

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Contact us
1300 363 400
+61 3 9545 2176
csiroenquiries@csiro.au
csiro.au

For further information
CSIRO Energy
Patrick Hartley
+61 3 9545 2595
patrick.hartley@csiro.au
csiro.au/energy

CSIRO Futures
James Deverell
+61 2 9490 8456
james.deverell@csiro.au
csiro.au/futures

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