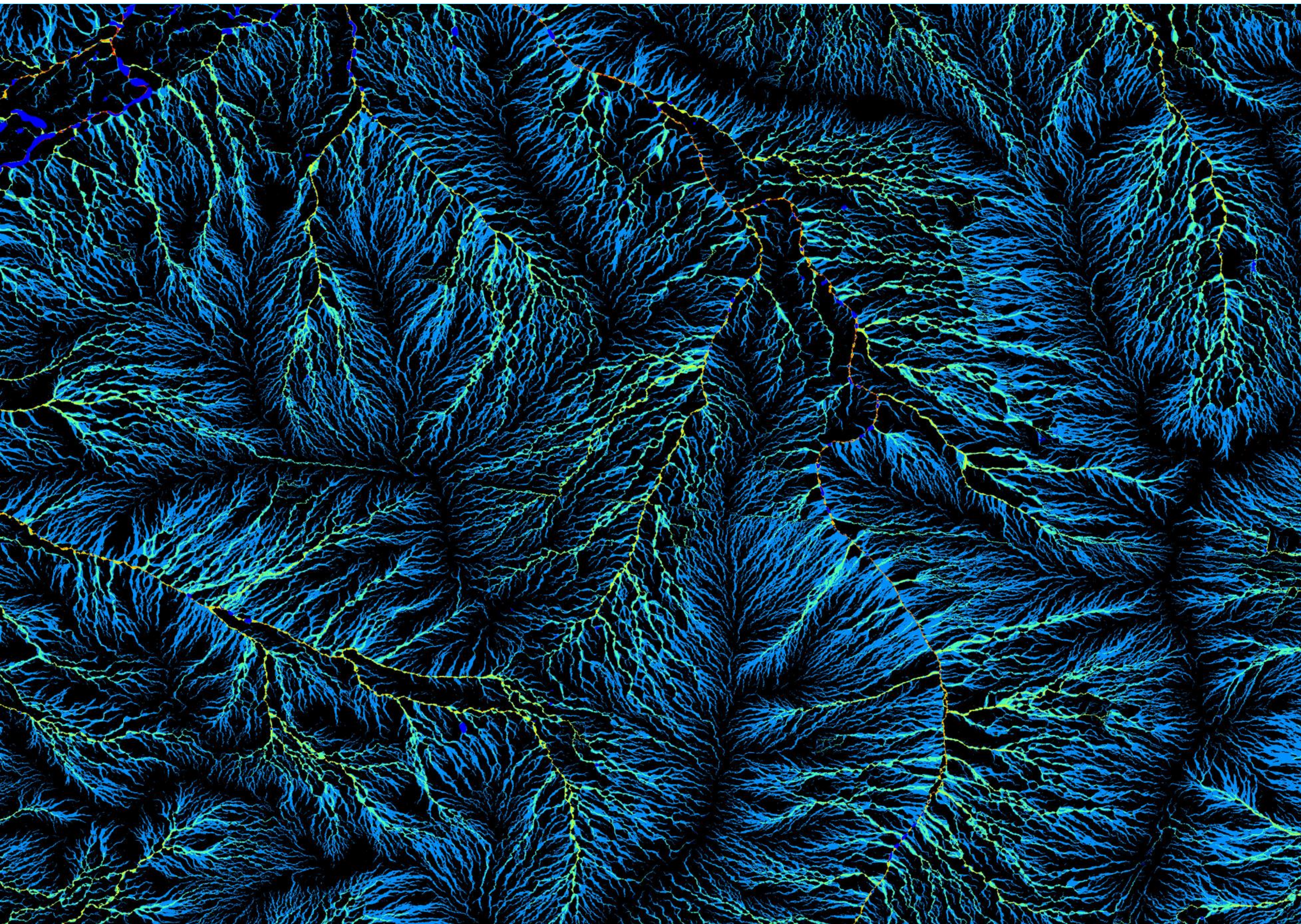
Australia's National
Science Agency

Hydrogen Research Development and Innovation

Global priorities in support of clean hydrogen industry development



Introduction

The need for, and potential of, clean hydrogen in supporting global decarbonisation pathways is increasingly recognised. In recent years, a large number of countries have published hydrogen strategies or roadmaps, and more are in preparation. These documents set bold ambitions for the development and deployment of clean hydrogen. Low-carbon hydrogen is starting from a low demand base, and present cost structures do not support a commercial business model. Research, development and innovation (RD&I) is at the core of efforts to unleash the potential for clean hydrogen.

This paper examines the RD&I priorities required to establish clean hydrogen as a key technology for the energy transition. The paper begins with a brief snapshot of the current status of policy and project momentum. This is followed by a review of seven hydrogen deployment-RD&I themes that align priority RD&I actions with major deployment themes included in hydrogen strategies. A review of trends in global hydrogen publications and patents information over the past decade follows, as a test of the status/evolution of RD&I activities.

The paper concludes that there is good reason to believe that progress is being made and that this will continue to grow; however, it will be critical for all nations with an interest in clean hydrogen to ensure that they nurture hydrogen RD&I through this decade and into the next, if the hydrogen industry vision which many have articulated is to be realised.

Hydrogen – a global snapshot

Hydrogen has emerged as an important element in the decarbonisation pathways of many economies. In recent years, over 30 countries, accounting for over 70% of global GDP, have either released, have in preparation (or are reported to have in preparation) national hydrogen-specific strategies, roadmaps or similar documents.[1]

Figure 1: National hydrogen visions, strategies and roadmaps

Many countries without specific hydrogen strategies are including hydrogen as part of their decarbonisation policies, including supporting demonstration and larger-scale projects. Hydrogen production ambitions represent a massive increase in production capability from present levels.

Flagship reports by the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) identify hydrogen (and its derivative fuels) as having a significant role to play in meeting global climate aspirations.[2]

Project announcements have mirrored this momentum. In mid-2021, project announcements with total associated investment through 2030 of around US$500 billion had been identified, an increase of over US$100 billion since the beginning of 2021.[3] Projects cover a wide spectrum of end uses – in exports, mobility, industry, infrastructure, etc.

The 'policy imperatives' woven into these various documents and announcements focus in large part on market activation and continued technology development; in transitioning from an emerging technology to commercial assets, akin to the recent experience in the solar PV industry.

While a number of 'policy imperatives' have been identified, a common theme within these policy imperatives is the critical importance of investment in RD&I with a focus on reducing costs and other barriers to hydrogen technology deployment.

[1] HyResource: Policy – International. Accessed 11 October 2021

[2] International Energy Agency (IEA, May 2021), Net Zero by 2050: A Roadmap for the Global Energy Sector. International Renewable Energy Agency (IRENA, June 2021), World Energy Transitions Outlook: 1.5°C Pathway.

[3] Hydrogen Council, Hydrogen Insights Update, July 2021. Accessed 11 October 2021

A strategic theme common to published strategies, roadmaps, etc. is the importance of long-term RD&I programmes in underpinning the development of hydrogen as a key technology in the energy transition, and especially in developing clean hydrogen technology solutions across the value chain that can be deployed at large-scale by 2030.

At the same time, strong international cooperation frameworks in RD&I can foster knowledge transfer and promote economies of scale, which can accelerate the uptake of promising emerging technologies; whereas weak cooperation mechanisms can slow down deployment of technologies in the demonstration phase by up to ten years or more (IEA, 2021).

Hydrogen deployment themes and RD&I priorities

In order to maximize its near term impact, RD&I actions that support market activation as well as progressing less mature, newer approaches for utilising clean hydrogen across diverse industry value chains (see Figure 2) have been identified and prioritised through the assessment of RD&I efforts of a number of countries. These key RD&I priorities and the deployment themes which they support are summarised in the following sections.

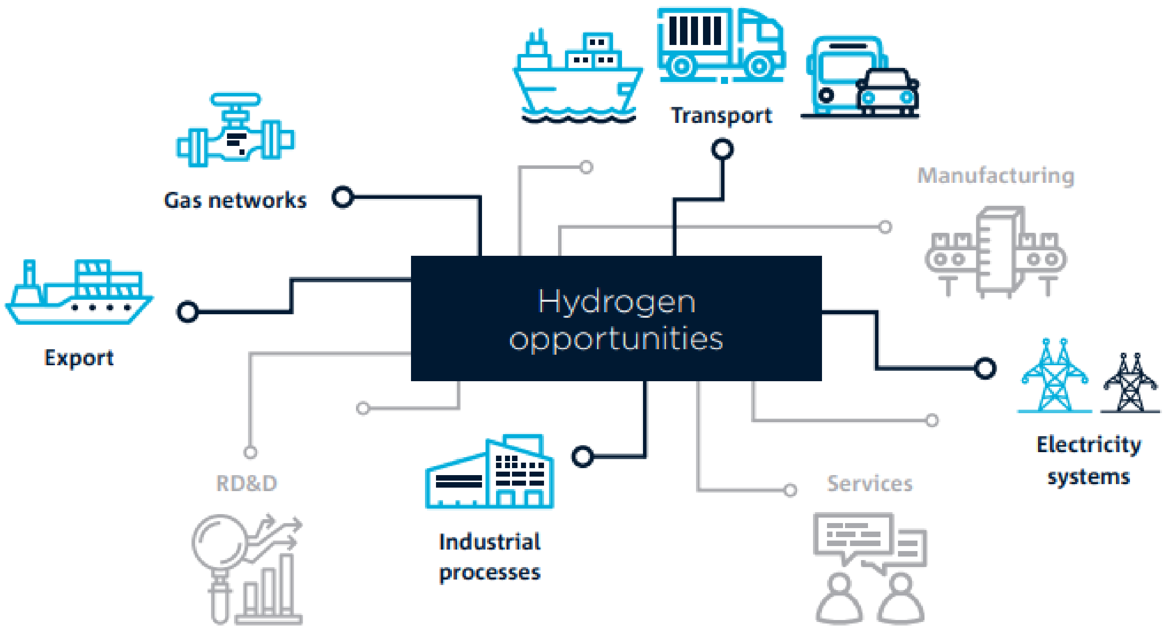


Figure 2: Hydrogen presents a decarbonisation opportunity across diverse industry value chains, and provides additional opportunities in associated sectors such as manufacturing and services.

Reproduced with permission from: Srinivasan, V., Temminghoff, M., Charnock, S., Hartley, P. (2019). Hydrogen Research, Development and Demonstration: Priorities and Opportunities for Australia

Deployment – RD&I Theme 1:

Significant reductions in clean hydrogen production costs over the course of this decade are pivotal to successful deployment.

Context:

Clean hydrogen production costs, especially for renewables-based hydrogen, are presently above those for hydrogen produced from unabated fossil fuels. At present, the cost of hydrogen produced from natural gas is in the range of US$0.50-1.70 per kilogram. Natural gas with carbon capture utilisation and storage (CCUS) entails a production cost in the range of US$1.00-2.00 per kilogram of hydrogen. Renewables-based hydrogen production cost is considerably higher, at US$3.00-8.00 per kilogram of hydrogen.[4]

Widespread commercial deployment and offtake of clean hydrogen by 2030 hinges on successful RD&I programs (including demonstration projects) that can quickly and significantly reduce cost. Target ranges for production costs have been declared by several countries and typically lie in the range of US$1-2 per kilogram of hydrogen.

Different countries envision different pathways for commercial clean hydrogen production; while renewables-based hydrogen production is the dominant production route in most plans, many countries are also aiming to produce hydrogen through fossil fuel conversion with CCUS and are supporting RD&I activities in this area.

Key RD&I priorities:

While there are several renewables-based production avenues, electrolysis is the key to scaled-up production in this decade.

Main focus areas include:

- Improvements in equipment - through increasing module size, stack density and lifetime, as well as low-cost catalyst systems.
- Improvements in materials - through use of fewer critical materials in electrolyser stacks and the creation of catalysts from less scarce materials.
- Scale-up and improvement in electrolyser manufacturing processes - through use of advanced manufacturing methods such as automation and digitalisation.
- Lower cost Balance of Plant designs and components, and durability improvements.
- Implementation of a suite of demonstration and larger scale projects in different operating environments, allowing development and operational learnings to inform future RD&I activities and the next phase of project developments.

While the main focus is on the more commercially mature PEM and Alkaline electrolysis production technologies, solutions at lower level technology readiness have also been identified as being of potential longer term significance, including:

- Emerging electrolysis technologies that have higher efficiencies and a broader acceptance of feedstocks (e.g. solid oxide electrolysis) or electrolysers that remove the need for precious metals (e.g. anion exchange membrane electrolysis).
- Hydrogen production through biomass conversion.
- Direct solar/thermal water splitting.
- Permeable membranes (that can improve hydrogen purity).

Turning to fossil fuel based clean hydrogen production pathways, CCUS is a critical enabler of low-carbon hydrogen production, especially in industrial applications, such as steam methane

[4] IEA, Global Hydrogen Review 2021, October 2021, page 113.

reforming of natural gas, in which CO_2 is emitted in a highly concentrated stream and represents lower-cost CCUS application opportunities.

CCUS technologies and applications have benefitted from considerable RD&I activities to date, with capture technologies in industrial applications demonstrated at scale having high average capture rates (of 80% or more).[5] Commercial arrangements, including those that manage risk across capture, transport and storage infrastructure, are of considerable importance for deployment; and there has been a gain in momentum in the outlook for hydrogen production with CCUS as supportive policies emerge – including, but not limited to, the United States, Norway, Netherlands, and Australia.

Main focus areas include:

- Improved CO_2 storage capabilities – through detailed site characterisation in key regions to assess feasibility of repurposing existing oil and gas infrastructure (pipelines, wells, geological formations) and the potential use of sub-sea installations, as well as significant further assessment work to convert theoretical storage capacity into "bankable" storage to support CCUS investment.
- Improvements in CO_2 capture process materials – through development of advanced capture media (solvents, sorbents and membranes) to reduce catalyst regeneration costs, and development of more energy efficient materials and advanced processes tailored for hydrogen separation.
- Linking with Direct Air Capture (DAC) technologies – through pursuit of CO_2 utilisation/storage solutions that capture CO_2 from the atmosphere or existing industrial emissions streams.

Deployment – RD&I Theme 2

Reaching full export potential and global supply chain development requires large-scale, low-cost hydrogen storage and distribution systems, and supporting infrastructure.

Context:

National strategies have identified a large potential for international trade in clean hydrogen. As production costs fall, improving volume or mass density of hydrogen through the use of hydrogen derivative carriers and improved compression and liquefaction technologies can help to reduce the costs for hydrogen storage, distribution and dispensing. Complementary cost reductions in these areas will help unlock global demand potential and boost activity in hydrogen supply centres.

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[5] The Quest project in Canada has demonstrated an average capture rate of around 80% since operations began in 2015. Quest annual summary - Alberta Department of Energy 2019

Key RD&I priorities:

- Advance systems for hydrogen storage through new supply chain technologies (including materials) for lowering costs, improving volumetric and gravimetric storage capacity and roundtrip process efficiency.
  - Examples include improving the separation of hydrogen from ammonia and liquid organic hydrogen carriers (LOHCs) through improvements in metal membranes and catalysts, and direct electrochemical synthesis of ammonia.
- Direct use of hydrogen carriers such as ammonia and methanol in applications such as power generation and chemicals production to reduce reconversion efficiency losses.
- Optimising large hydrogen storage and distribution infrastructure between production facilities and loading sites/ports, including through new underground hydrogen storage approaches.
- Advancing the potential for liquefied hydrogen use through:
  - Improving liquefaction efficiency, including through control of vaporisation rates, and improved heat exchangers and coolants, insulation, and in compression technology.
  - Scaling up of tanks and improved thermal insulation materials and systems.
  - Large-capacity vaporisers, boosting pumps, piping and joints, and loading systems.
  - Developing, testing and demonstrating carrier vessels for long distance seaborne transport.
- Development of high-throughput compressors, low-cost materials and novel technologies to lower energy and other supply chain costs of high pressure, storage and distribution systems, including for dedicated hydrogen pipeline distribution and transmission networks.
- Supply chain architecture, design and operations.

While these priorities have been framed in the context of supporting the expansion of a global trade in hydrogen, they can also act to unlock domestic demand potential that otherwise may have been slower to eventuate. Additionally, improvements in the large-scale storage of hydrogen and its carriers may help provide a long term energy storage solution to support the increased penetration of variable renewable energy into energy systems.

Deployment - RD&I Theme 3

Mobility applications targeted for initial deployment will be greatly assisted by improvements in fuel cell technologies and refuelling infrastructure; RD&I efforts will support the longer term use of hydrogen and hydrogen-based fuels in marine and aviation applications.

Context:

Together with the industry sector, mobility (transport) applications represent the largest near term end use demand for clean hydrogen.

Mobility applications are included in all national strategies, and emphasised in many. Plans in the Asian region encompass a wider range of mobility options (passenger vehicles, trucks, buses/commercial vehicles, etc.) while those in Europe tend to be directed more towards heavy, long-range transport uses (where hydrogen is considered to be closest in cost competitiveness against diesel and is more competitive against battery electric vehicles).

Opportunities for other heavy transportation systems such fuel cell trains and mining heavy haulage are in development. Hydrogen and hydrogen-carrier options (e.g. ammonia, synthetic fuels such as e-methanol) are also in development for maritime and aviation transport.

Key RD&I priorities:

- Improving (automotive) fuel cell technologies through, for example:
  - New fuel cell materials (e.g. membranes, catalysts) with lower costs, enhanced durability, stability and lifetime, as well as ability to operate at higher temperatures.
  - Embedded storage and systems to optimise performance costs in mobility.
  - Improved component integration and stability, lifetime and tolerance to impurities.
  - Optimisation of electrical performance and durability.
  - Developing manufacturing processes for high-speed, high-throughput production, and quality assurance.
  - Improved hybridisation (e.g. with batteries or supercapacitors) and optimised system design.
  - Demonstrating fuel cells in trains and localised marine applications.
- Optimisation of refuelling infrastructure through, for example:
  - Development of larger on-site storage systems, integrated with supply and (higher rate) refuelling infrastructure.
  - Lower-cost equipment for ultra-high pressure hydrogen stations.
  - Reducing cost of compressors and high-pressure vessels (e.g. polymer materials, higher temperature refuelling methods).
  - Development of liquid hydrogen refuelling station technology.
- Investigation of hydrogen and carrier options for the harder to decarbonise mobility sectors such as maritime and aviation, including challenges surrounding new supply chains and refuelling infrastructure, and how 'onboard' storage would be optimised.
- Deployment of demonstration projects across mobility applications to inform RD&I programs and the next phase of project developments.

Deployment - RD&I Theme 4

Substitution of clean hydrogen as a fuel and chemical feedstock in industrial processes (e.g. ammonia, chemicals production, and steel making) will be a key driver of hydrogen demand.

Context:

Hydrogen produced from unabated fossil fuels is presently used as a feedstock in several industrial processes and, subject to cost considerations, can be displaced by clean hydrogen. Near term 'low hanging fruit' opportunities lie in substituting clean hydrogen in these processes, including ammonia production and petroleum refining.

Other hard-to-abate industrial processes require sustained RD&I efforts to develop new approaches for utilising clean hydrogen to displace incumbent fossil fuels. These include low carbon pathways to chemical and plastics feedstocks such as the use of methanol, which can be produced in conjunction with CCUS. Increasing attention is being devoted to hydrogen in steel making, metals processing (refining) and cement manufacture. Steel making, for example, accounts for 7-9% of global anthropogenic CO_2 emissions.

Key RD&I priorities:

- In steel making, opportunities for use of hydrogen include:[6]
  - The development of breakthrough hydrogen reduction technology, seeking to eliminate direct greenhouse gas emissions from the ironmaking process.
  - The transitional use of hydrogen by blending it with fossil-based reductants, using it in conventional steelmaking processes (blast furnace and direct reduced iron) to reduce emissions.
  - Testing natural gas-based direct reduced iron with high levels of hydrogen blending.
- Displacement of fossil fuels (particularly oil and gas) by hydrogen for industrial process heat purposes (e.g. in alumina, cement manufacture) including the analysis and development of new burners and kilns, or the creation of synthetic chemicals and fuels (e.g. methanol derived from CO_2 and hydrogen).
- Implementation of demonstration projects over the course of this decade to accelerate uptake of new technologies.

Deployment – RD&I Theme 5

Hydrogen substitution in domestic and industrial gas uses through the blending of hydrogen in gas networks is an important early deployment avenue, with the potential to eventually ramp up to 100% hydrogen in such networks, and requires RD&I actions to understand impacts on pipeline and network materials, domestic and commercial appliances, and metering systems.

Context:

Existing natural gas pipeline and network infrastructure can act as an early large-scale offtake opportunity for hydrogen. Blending hydrogen into gas networks can facilitate demand growth, support cost-reductions in production technologies and build community awareness.

[6] World Steel Association, Fact sheet Hydrogen (H2)-based ironmaking, July 2021.

Moreover, repurposing gas pipelines infrastructure can significantly reduce the cost of establishing national and regional hydrogen transmission and distribution networks, and extends the life of existing network assets as part of the clean energy transition.

Several demonstration projects are underway or planned, and together with RD&I efforts, will lead to better understanding of the impact of blended gases and 100% hydrogen on pipeline and network infrastructure.

Key RD&I priorities:

- Understanding network and pipeline effects of hydrogen and blended gases, including on steel pipeline and component materials performance.
- Improved predictive modelling to ensure safe and efficient operation of hydrogen network infrastructure, including for fracture control, fatigue management, and related impacts.
- Development of advanced infrastructure protection and repair systems, including development of protective coatings for internal surfaces.
- Smart sensing, monitoring and inspection technologies to support measurement and accounting of different blending concentrations, and to provide data on system integrity and maintenance.
- Understanding compatibility (in particular combustion properties) of appliances and equipment with hydrogen fuel at varying concentrations, including solutions for new/modified household and industrial equipment to allow for a broader range of fuel compositions.
- Development of de-blending technologies to control hydrogen levels in different parts of the network.
- Development and deployment of 100% hydrogen (ready) residential and commercial appliances, as well as industrial equipment.
- Development of innovative materials for use in new hydrogen pipeline infrastructure, including facilities.

Deployment – RD&I Theme 6

Hydrogen can support faster uptake of renewables in electricity systems through 'balancing services' and short term network stability support, requiring advances in fuel cell, turbine/engine and storage technologies, and better understanding of grid integration issues.

Context:

Several countries recognise hydrogen's potential as a low-carbon option for co-generation and for providing flexibility and grid stability as they reach high shares of variable renewable power.

Hydrogen can be used as a fuel in reciprocating gas engines and gas turbines. Stationary fuel cells can also provide backup power and off-grid electricity. Electrolysers can be employed as flexible load. Ammonia could also become a low-carbon fuel option for the power sector; it can be used directly or converted to hydrogen for use in gas turbines, used directly in internal combustion engines or fuel cells, or fed into coal power plants in a co-firing arrangement.

Key RD&I Priorities:

- Hydrogen and ammonia gas turbine activities include:
  - Enable a wider range of acceptable hydrogen concentrations through, for example, burner developments.
  - Develop new materials, coatings, and cooling schemes.
  - Improved understanding of combustion behaviour and optimisation of components and gas mixtures for low NOx combustion.
- In addition to the (mobility) fuel cell RD&I priorities mentioned earlier, stationary fuel cell activities include:
  - Materials research to reduce cost and address issues related to high-temperature operation and lifetime, particularly in solid oxide systems.
  - Minimising or eliminating the use of precious metals to reduce costs.
  - Eliminating/reducing causes of degradation.
- Research into conversion of internal combustion engines to use hydrogen or ammonia as a fuel.
- Stationary hydrogen storage technologies that can support long term or seasonal storage requirements (see also RD&I Theme 2).
- Benefits/challenges to the electricity network and for electrolyser operation of electrolyser flexible load (rapid 'ramping') characteristics.

Deployment – RD&I Theme 7

National strategies highlight the importance of progressing 'cross-cutting' research activities in a time scale that is complementary to technology, demand and supply chain advancement.

Context:

Development of a clean hydrogen industry will not be based on individual technology or singular aspects of, or achievements within, the value chain. Numerous considerations must be understood concurrently.

Cross-cutting research in fields such as the environment, social license and safety, policy and regulation, techno-economic modelling, etc. is required across the whole hydrogen value chain (and are applicable to all deployment RD&I themes noted above).

Key RD&I priorities:

- Social license, safety and standards, including:
  - Continued development and revision of codes and standards.
  - Improved sensing and contaminant detection, safety management risk assessment tools development, safety lessons-learnt identified and shared.
  - Understand, engage and inform community attitudes.

- Policy and regulation, including:
  - reviews of existing policies and regulation to identify barriers across the value chain, supporting development of appropriate updated regulations.
  - Supporting the development of domestic and internationally accepted classifications to support hydrogen accreditation or Guarantee of Origin schemes.
  - International standards for hydrogen technologies to allow easier uptake and integration of those technologies globally.
- Environment, including:
  - Water and land use assessments.
  - Verification and monitoring to demonstrate ongoing integrity.
- Modelling, including:
  - Techno-economic modelling of value chain configurations.
  - International supply chain analyses, including studies into trade partnerships, value chain technology options, and business models for global supply chains.
  - Planning and operation of integrated energy systems.
- Ancillary technology and services, including:
  - High-speed manufacturing techniques, additive and automated manufacturing/assembly techniques.
  - Sensors and other technologies to reduce manufacturing defects.
- Skills development, including:
  - Identify gaps and analyse skill requirements across the value chain.
  - Identify required training and education.

Summary RD&I highlights

Headline RD&I priorities based on the preceding analysis is as follows:

- Upscaling to larger size, more efficient and cost-effective hydrogen electrolysers offers one of the biggest RD&I opportunities in the global energy system over the next ten years, especially if the technology is to make an important contribution to reductions in global CO_2 emissions in the coming decades.
- Developing large-scale storage, distribution, and dispensing systems is critical in advancing high volume international hydrogen trade flows, especially over long distances.
- Continued development of fuel cell mobility solutions and upscaling of refuelling infrastructure for road transport applications, especially in the heavy and/or long distance market segments, can kick-start initial demand.
- Blending of hydrogen into existing natural gas networks/repurposing existing pipeline systems into dedicated hydrogen transmission infrastructure can spur demand growth but requires supporting RD&I activities to better understand and manage pipeline network and appliance impacts.

- Long term RD&I support is vital for the development of hydrogen solutions in difficult to decarbonise heavy industry and mobility applications such steel production, metals processing, seaborne transportation and aviation.
- Further development of gas turbines, stationary fuel cells, and of ammonia engines and turbines which support hydrogen's potential as a low-carbon option for co-generation, and for providing flexibility in power systems as economies reach high shares of variable renewable power.
- Research in 'cross cutting' areas to support standards and safety, appropriate regulatory reforms and domestic and international hydrogen production emissions certification schemes, environmental impacts of projects, and studies of global supply chain business models and social and labour market impacts.

Hydrogen RD&I capabilities

Publications and patents are important mechanisms through which the results of scientific and technological endeavours are disseminated to a global community. Not only are publications and patents an important component of direct knowledge generation and dissemination, they are also rich information sources to further progress research and innovation through, for example, the ability to source author/inventor names, institutional affiliations, references and citations, etc.

A review of trends in global hydrogen supply chain-related publications and patents information can therefore act as a test of the status or evolution of RD&I activities.

Key points from an examination of global hydrogen publications and patents data for the period 2010-2020 is presented below. It should be noted that the collected data is sensitive to the search strategy and key words developed to determine the publications and patent landscape.[7]

While specific numbers are provided for emphasis in the commentary below, the observations should best be viewed as indicative of directional trends.

Global hydrogen publications

Global trends in hydrogen publications as a function of supply-chain area are shown in Figure 3 overleaf.

Reflecting the key deployment theme of the importance of reducing the cost of hydrogen production, publications output related to hydrogen production dominates (around 60,000 publications over the period 2010-2020) against approximately 40,000 publications for utilisation and 18,000 for storage and distribution.

In the decade to 2020, annual publications output (on the search criteria used) has more than tripled for hydrogen production, rising from 2,686 publications in 2010 to in excess of 8,800 in 2020.

[7] The search strategy and key words can be found in Charnock S., Temminghoff M., Srinivasan V., Burke N., Munnings C., Hartley P. (2019) Hydrogen Research, Development and Demonstration: Technical Repository, CSIRO (pages 98-106).

Over the same period, publications output has roughly doubled in the case of both utilisation (2,358 publications in 2010 to 4,750 in 2020) and storage and distribution (1,173 publications in 2010 to 2,147 in 2020).

Growth in publications output has been strongest in hydrogen production over the past decade, which has exhibited a broadly consistent output growth profile over the 2010-2020 period. The search strategy is also suggestive of an uptick in publications output in the second half of the decade (compared to the first half) for the storage and distribution and utilisation supply chain elements.

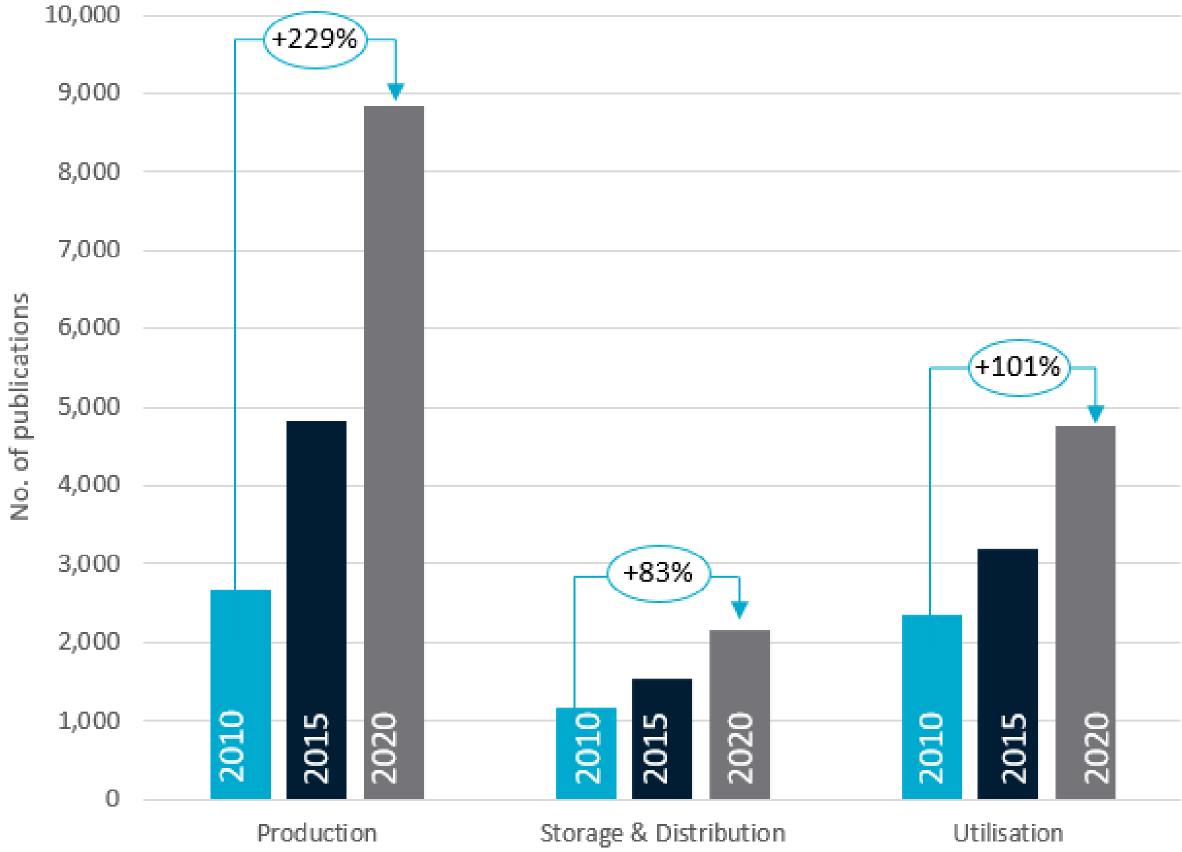

Figure 3: Global hydrogen publications output by supply-chain area[8]

[8] There will be some overlap of key words searched across the supply chain areas, indicating that an overall hydrogen publications output tally would not align perfectly with a simple aggregation of the individual areas. The key words search structure developed is intended to lessen this overlap.

Global hydrogen patents

The global patents landscape is comprised primarily of private companies that are patent assignees, while some universities and research institutions also hold patents to a lesser degree. Figure 4 highlights patent-family filing trends over the period 2010-2019, using the first filing in a patent family.[9]

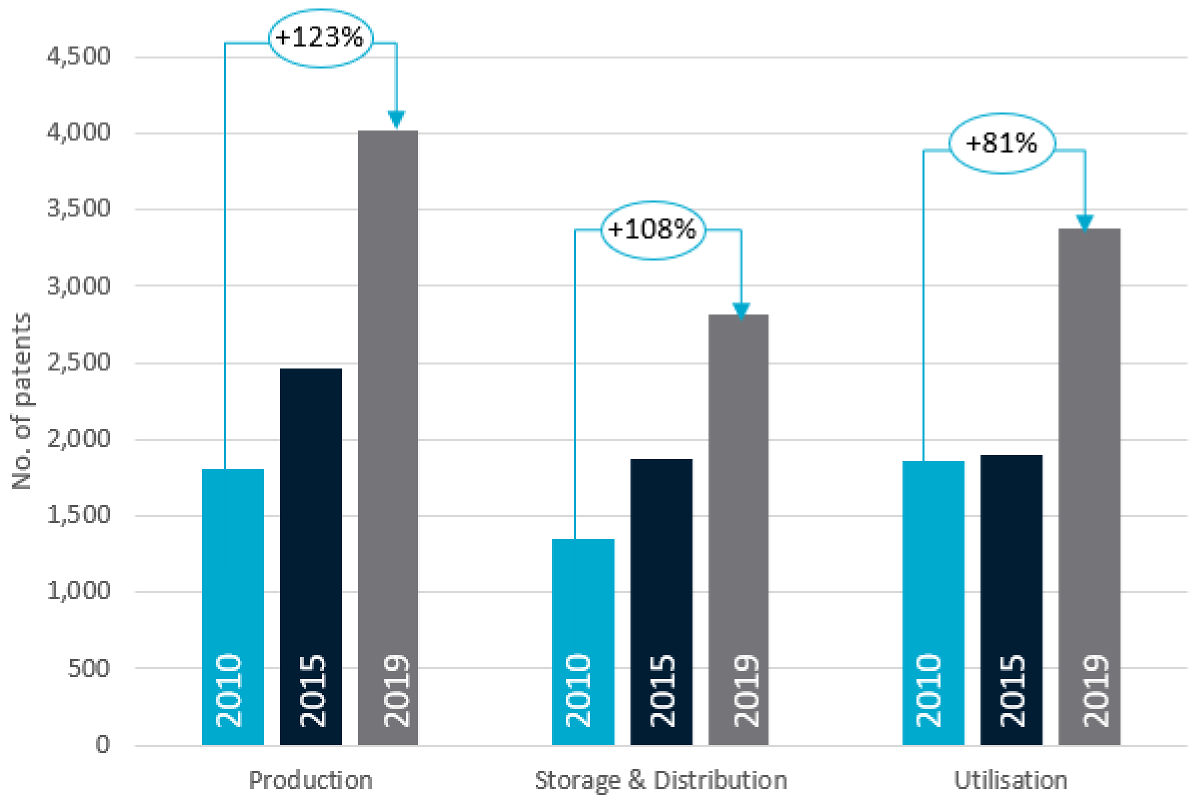

Figure 4: Global hydrogen technology patent filing over time

The count of patent families across the hydrogen value chain, after a period of virtual stagnation in the first part of the last decade, has exhibited a noticeable increase since around 2014/2015, and particularly in 2018/2019. The range of patents across value chain areas is more evenly distributed than for publications output.

Overall, the publications and patents data suggests an increased pace of knowledge enquiry and innovation in hydrogen-related areas since the middle of the last decade, which likely is reflective of the recent uptick in government and industry investment in hydrogen industry development.

RD&I output as indicated by publication metrics has to date emphasised hydrogen production innovation, presumably because this is the area with the most tangible impact on hydrogen technology cost competitiveness. Moving forward, it seems reasonable to suggest that the areas of hydrogen storage, distribution and utilisation will show increased RD&I intensity, since innovation in these areas will be needed to both build hydrogen demand, and complete the 'hydrogen supply chain jigsaw'.

[9] 2019 is chosen as the end period for review as 2020/20201 patent filing data is not fully complete due to the delay in patent filing/approvals.

Further detailed analysis of publication and patent data should reveal more detailed conclusions regarding RD&I focus globally but such an analysis is outside the scope of this report.

Summary and conclusions

Hydrogen is a versatile energy carrier which can be used in diverse industry and domestic applications, as evidenced in the deployment themes indicated in this report. Many of the ways in which hydrogen can be used are not common today. RD&I efforts will enable the clean energy transition of many existing and new energy value chains, thereby making a significant contribution to national and global decarbonisation pathways.

RD&I priorities across the hydrogen value chain are generally well identified and align with industry and government priorities. What needs to be done in which areas is either well understood or that understanding is building.

The more important and difficult question is concerned with how well global RD&I efforts are addressing these priorities. There is good reason to believe that progress is being made. Science and innovation output is building, and demonstration projects are emerging across the globe. Significant public and private funding commitments are emerging to support both hydrogen RD&I and hydrogen technology deployment.

There is good reason to believe that hydrogen-related RD&I intensity will continue to grow and enable the next wave of global hydrogen industry development. However, it will be critical for all nations with an interest in clean hydrogen to ensure that they nurture hydrogen RD&I through this decade and into the next, if the hydrogen industry vision which many have articulated is to be realized.

At the same time, the mental image most often associated of RD&I activities is of technological advances - improvements in electrolyser efficiency, in fuel cell performance, and so on. The speed with which these advances can be developed and deployed, however, is also critically a function of:

- Strong connection, collaboration and knowledge sharing within and across borders, as well as strong connections between the research community and industry to better understand industry needs. Amongst other things, this will avoid duplication of effort.
- Advances in ‘cross-cutting’ research areas that are non-technology related and often a necessary requirement in progressing technological advances into widespread technology deployment.

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